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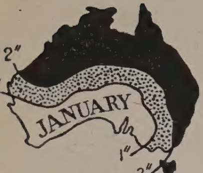
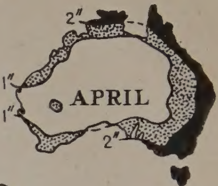
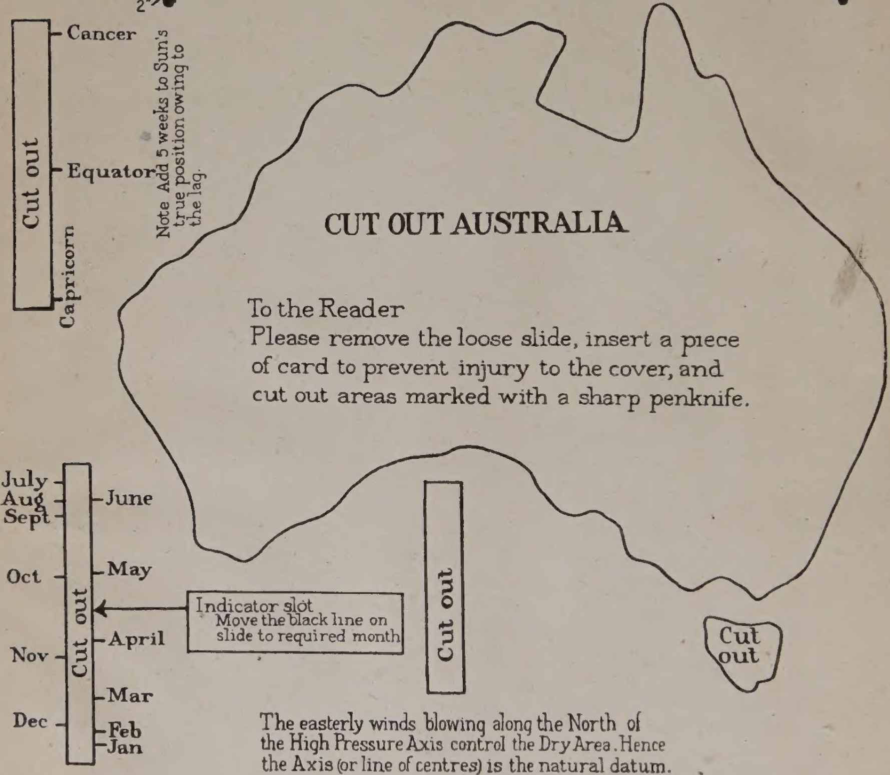
SOLAR-CONTROL MODEL

Showing the relation between the Sun's change in declination, the position of the Anticyclone Belt, the permanent winds, and the Monthly Rainfall in Australia





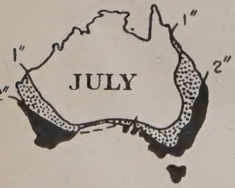


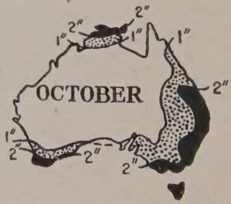
Note Add 5 weeks to Sun's true position owing to the lag.

To the Reader
Please remove the loose slide, insert a piece of card to prevent injury to the cover, and cut out areas marked with a sharp penknife.

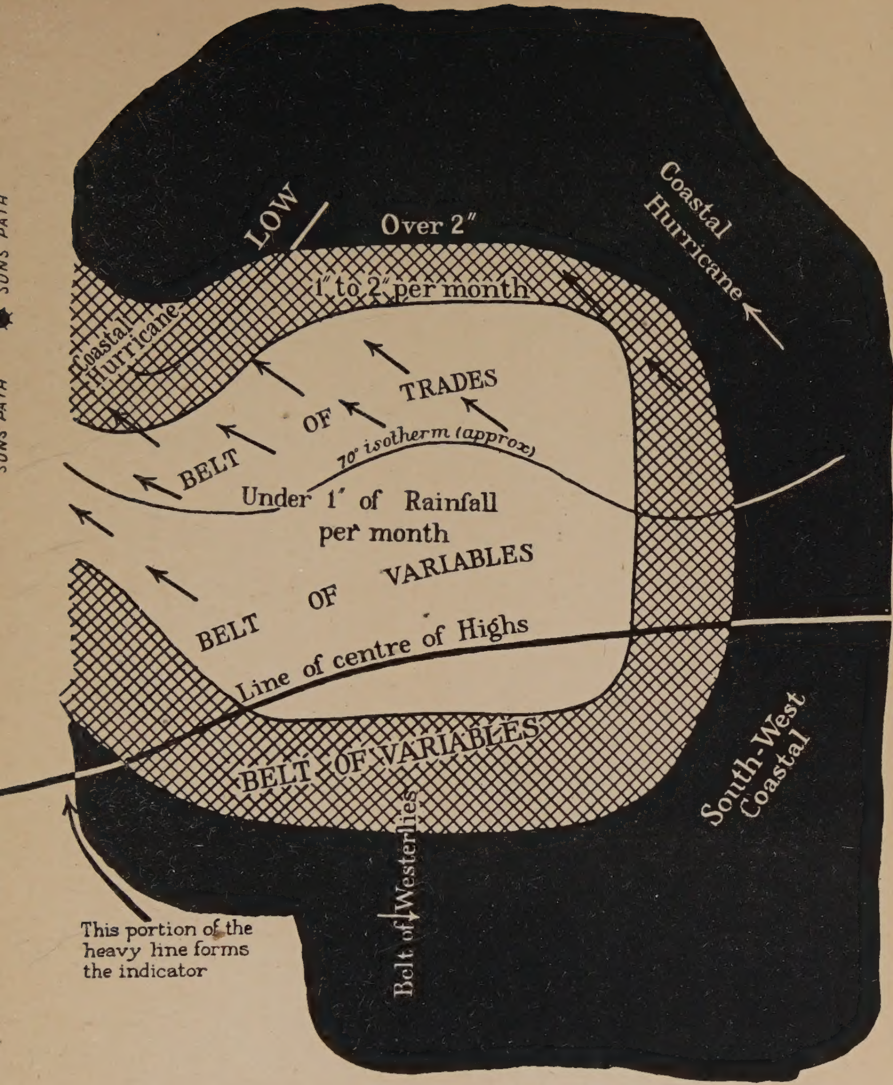
Indicator slot
Move the black line on slide to required month

The easterly winds blowing along the North of the High Pressure Axis control the Dry Area. Hence the Axis (or line of centres) is the natural datum.





With acknowledgements to H. A. Hunt's rotating rain clock


SUNS PATH
SUNS PATH
LOW
Over 2″
Coastal Hurricane
1″ to 2″ per month
Coastal Hurricane
BELT OF TRADES
70° isotherm (approx)
Under 1″ of Rainfall per month
BELT OF VARIABLES
Line of centre of Highs
BELT OF VARIABLES
South-West Coastal
Belt of Westerlies
This portion of the heavy line forms the indicator

AUSTRALIAN METEOROLOGY

A TEXT-BOOK INCLUDING SECTIONS ON AVIATION AND CLIMATOLOGY

BY

GRIFFITH TAYLOR
D.Sc., B.E. (Syd.); B.A. (Cantab.), F.G.S., F.R.G.S.
PHYSIOGRAPHER IN THE COMMONWEALTH WEATHER SERVICE
INSTRUCTOR IN THE UNIVERSITY OF MELBOURNE; AND
LECTURER AT THE COMMONWEALTH FLYING SCHOOL

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PREFACE

This text-book has developed partly from the series of lectures which I have given since August, 1914, to the aviators at the Commonwealth Flying School, and partly from a more extended course at the University of Melbourne.

Similar books written for British or American readers, quite apart from their lack of local application, are somewhat confusing to Australian students, for the fundamental rules dealing with wind circulation have all to be reversed in the southern hemisphere. Moreover, our latitudes are much lower than those of either of the two countries cited, so that many of our problems belong to tropical meteorology.

Teachers in High Schools will find that the following chapters—omitting the small type—will form a fairly complete study of Australian meteorology, suitable for the University public examinations:

Chapters II, III, V, VI, VII, VIII, X (*Law* only), XI, XII, XIII, XIV, XVII, XXIII, and XXVI.

Meteorology—especially the study of rainfall—is of such paramount importance in Australia that I hope the general public, especially farmers and pastoralists, will make use of this book. They will, I believe, be interested in the historical chapter (I), the study of the weather chart (II), and the work at a small station (III). The peculiarities of our rainfall are treated in Chapters XII to XIX. Our special storms and hurricanes are discussed in Chapters XX and XXI. Three somewhat novel sections are those describing the actual procedure in upper air research, the discussion of long-distance forecasting and weather cycles, and lastly the application of meteorology to aviation.

The aviation data are based partly on my own experience, and partly on numerous essays which I have obtained from the aviators during the twelve schools with which I have been associated. So far as I am aware, no text-book has yet appeared in which this very important aspect of the science is treated in the same detail. Suggestions to guide the aviator's study of meteorology are given in Chapter XXV.

I have quoted authorities throughout the book, but it is fitting to acknowledge how much help I have derived from American memoirs, especially those of the Weather Bureau at Washington. The papers by Humphreys, Blair, and others, and the writings of Ward and Huntington, have been largely drawn upon.

The text-books which I have found most useful are Milham's *Meteorology* and Hann's *Meteorologie,* and I have made numerous references to them.

The English writers Sir Napier Shaw and W. H. Dines have been extensively consulted in the sections dealing with upper air research and with the modern theory of the origin of the atmospheric eddies. I have ventured to describe in some detail in Chapter XVIII certain summer weather types which seem to me to illustrate the theory of the origin of Lows near the isothermal layer.

My indebtedness to my colleague Mr. E. T. Quayle, B.A., especially in the sections dealing with clouds and their significance, will be obvious. He has also kindly read the proofs.

I have to thank the Commonwealth Meteorologist for permission to publish this book, for it is necessarily based on the records in the Central Weather Bureau. The greater part of the manuscript has, however, been written in my leisure hours during the past three years.

If some of the illustrations should appear somewhat crude, it is because the author prefers in general to use his own drawings rather than risk the errors which would be sure to creep in if the figures were prepared in England. For similar reasons, textual errors are difficult to eliminate when the author is at one side of the globe and the printer at the other. The indulgence of the reader is requested in this connexion.

GRIFFITH TAYLOR.

MELBOURNE
1 *Nov.* 1918.

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CHAPTER I

THE GROWTH OF METEOROLOGY[1]

There is no better way of obtaining a clear picture of a new science than by following the path along which the pioneers have trod in their search for the principles on which the science is based. Hence I need offer no apology for commencing this study of Australian meteorology by a brief discussion of the history of meteorology.

It has been well stated that there are four periods in the growth of the science.

A. Antiquity to 1590 A.D. Crude surmises. No instruments.

B. 1590–1774. Instruments render observation accurate.

C. 1774–1849. Logical explanations of many of the principles.

D. 1849 onwards. Weather Bureaux. Rigid testing of theory.

Period A. Several thousand years before Christ the Chaldean soothsayers based their prophecies on weather signs. Thus we read that ‘ When it thunders in the day of the moon's disappearance, the crops will prosper and the market will be steady ’. This is signed *Asaridu* ; and there are pseudo-scientific descendants of this soothsayer, at about the same level of intelligence, living to-day.

Aristotle, who lived in the fourth century before Christ, was much interested in weather conditions, and both he and his disciple Theophrastus wrote essays dealing with winds and rain.

To England must be given the credit of one of the oldest meteorological logs. William Merle of Oxford (1337–44) kept a record of the weather ; apparently, however, to prove his astrological theories rather than for meteorological purposes.

We are told that King Sejo in Corea invented the first rain-gauge about 1442, but much similar primitive apparatus had no doubt also been used elsewhere and then forgotten.

---

[1] The chief authorities for this chapter are Hellmann, ‘The Dawn of Meteorology ’, *Journal Meteorological Society*, London, 1908 ; Rotch, *Sounding the Ocean of Air*, London, 1900 ; Noble, ‘ Development of Meteorology in Australia ’, *Monthly Weather Review of U.S.A.*, November 1905 (p. 480) ; Todd, *Meteorological Work in Australia*, Aus. Assoc. Adv. Science, Adelaide, 1893.

With the dawn of printing, books on Prognostics and Wonders were published, having reference to weather signs. For example, Caxton in 1481 and Fulke in 1563 issued such books. We are told that the latter writer's book on 'Ayer and his Nature' went into eight editions!

Period B. In Italy the Renaissance of learning was marked by the activity of Galileo and his school. Somewhere about 1590 either the master or Sanctorius his pupil devised a thermometer at Padua. Some fifty years later (in 1643) Torricelli invented the other mainstay of the science—the barometer. Ten years later Ferdinand, the enlightened ruler of Tuscany, had twelve meteorological stations scattered through Northern Italy, while Castelli about this time made perhaps the first practical rain-gauge.

In 1622 that intellectual giant, Francis Bacon, had written a book on the winds, and in 1648 Pascal caused the barometer to be tested on Puy de Dôme. He found that the column of mercury fell three inches as the mountain was ascended.

In 1714 Fahrenheit of Dantzig used mercury in the thermometer and fixed his peculiar zero and scale. Celsius followed with his Centigrade scale in 1742.

In 1752 America enters the scene. Benjamin Franklin carried out his famous lightning experiments, and made shrewd suggestions as to the causes of many important phenomena:

Period C. In 1774 Priestley showed that air is not one of the four so-called 'elements'; for he discovered that it was a mixture of gases, of which oxygen was the chief.

About this time ballooning gave an impetus to the study of meteorology. In 1783 Charles rose 9,000 feet above Paris, and in 1784 Jeffries in England found that the temperature decreased about 1° for each 360 feet on his ascent of two miles. In 1804 the French scientist, Gay-Lussac, rose 23,000 feet in a balloon.

In 1801 Lamarck proposed the classification of clouds, and the great German geographer, Humboldt, first drew isothermal lines for the world in 1817.

In 1822 meteorology commenced in Australia, but it will be more convenient to discuss local history in a separate section.

Period D. In 1849 telegraphy was advanced enough to place an economic weapon in the hands of meteorologists. Henry in America and Glaisher in England both realized the value of telegraphic news about this time. In 1851, at the Great Exhibition, weather maps based on such data were sold at a penny.

In 1853 perhaps the first notable theoretical work was published, by the American Ferrel, on the *Circulation of the Atmosphere.*

In 1854 Fitzroy was put in charge of the first 'bureau' (in connexion with the Board of Trade) in London. His early work related chiefly to storms as affecting shipping.

In 1854 a furious storm swept the Crimea and caused the loss of the *Henri IV*. This storm was investigated by Leverrier, who showed that it travelled eastwards from France, and could have been forecasted by telegraph.

In 1860 Fitzroy used the telegraph for such warnings, and in 1861 forecasts were issued, and continued until 1867; while in 1875 a weather map appeared in the London *Times*.

Upper Air Research. The most notable development in meteorology has been the detailed exploration of the upper air. This may be dated back to 1882, when Archibald used kites to measure wind velocities up to a height of 1,200 feet. In 1891 Bonvallet sent off 97 paper balloons from Amiens, many of which were recovered, and indicated the path of the winds. In 1893 a meteorograph (or self-recording apparatus) was sent up by balloon from Besançon, and in 1894 Assmann's *ballon sonde* (sounding balloon) reached a height of 13½ miles and recorded a temperature of 54 below zero. In 1896 the Americans at Blue Hill used the Hargraves kite (invented at Sydney) with very good results.

To the French belongs the chief discovery of recent meteorological research. In 1901 Teisserenc de Bort announced, from his study of the records obtained by small balloons, that the temperature ceased to fall after a certain height was reached. This isothermal layer was found to be about ten kilometres above sea level.

In 1907 Dines invented his light and inexpensive meteorograph, which has enabled hundreds of accurate records to be obtained at comparatively slight cost.

In 1911 Simpson used these instruments to test the conditions of the upper air in Antarctica.[1] There is no doubt that this region of the wildest weather of the globe is of great importance in the meteorology of the southern hemisphere, and Simpson's records have already proved of great interest.

With the outbreak of war, aviation and meteorology have become closely linked. Meteorologists both in U.S.A. and Australia have described flights made in October 1915. Probably other similar flights occurred earlier elsewhere.

Australian Meteorology

As at present, meteorology interested many people early in the nineteenth century who were not professionally engaged in scientific work. In 1822 Sir Thomas Brisbane, Governor of New South Wales, had a private observatory at Parramatta, where he kept a meteorological record from October 1822 to March 1824.

From 1832 to 1838 Dunlop, as 'Imperial Meteorologist', was in charge of the Parramatta station, while Captain King kept records of pressure, temperature, and humidity from 1832 to 1848.

In 1840 three other stations were instituted, at South Head (Sydney), at Port Macquarie (New South Wales), and at Port Philip. These were in charge of convicts who had been trained at the Parramatta station, and were maintained for a number of years.

In 1842 the Rev. W. B. Clarke contributed no less than twenty-one articles to the Sydney *Morning Herald*. Even in these enlightened days I doubt if a daily paper can beat this record! Clarke also contributed many valuable papers to the Royal Society of New South Wales from 1839 to 1858, and in 1846 he advanced the 'nineteen-year cycle' theory of recurring seasons.

In 1854 Williamstown was made a station, and from 1858 to 1863 the famous German Neumayer was in charge of the Melbourne station.

In most of the states the meteorological work at first was affiliated with astronomical work, but of late years this connexion has almost everywhere been severed.

---

[1] The writer was commissioned by the Commonwealth to study especially such scientific aspects of Antarctic research as would be of value to Australia. Although primarily doing geological work, he assisted Dr. Simpson in some of the balloon experiments, and was in charge of the meteorological station in Dr. Simpson's brief absence on a sledge journey.

In 1856 Charles (later Sir Charles) Todd was in charge of the Adelaide records, while Ellery succeeded Neumayer in Melbourne in 1863. In 1877 Russell published a daily weather map in the Sydney *Morning Herald*, and ten years later Egeson (temporarily in charge) commenced to publish daily forecasts. In 1876 weather data were collected at Perth by the Survey Office. In 1887 Clement Wragge took charge of the Brisbane bureau.

In 1906 the work of the various state bureaux was amalgamated by Act of Parliament ; and in January 1907 the Commonwealth bureau at Melbourne was instituted. Mr. H. A. Hunt, who had been in charge of the state bureau for New South Wales, was appointed Commonwealth Meteorologist.

CHAPTER II

THE WEATHER CHART

Australians are in a peculiarly fortunate position in that almost all the leading newspapers publish a daily weather chart. This fact always excites the envy of visiting meteorologists—and we may well commence our study of Australian meteorology by learning how the weather charts are made, and what they show us.

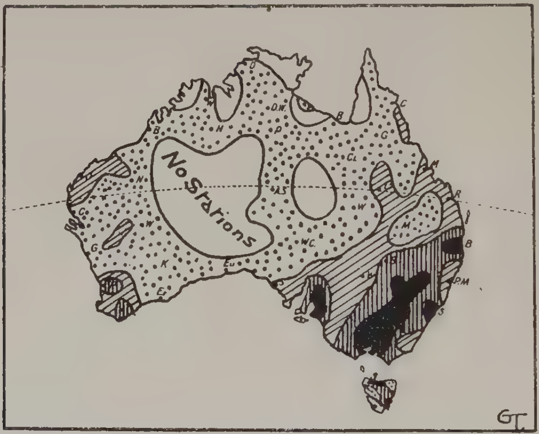

Fig. 1. General distribution of rainfall stations (based on the large wall map by H. A. Hunt, 1910). In the black areas the stations are approximately 10 miles apart; in the dotted area more than 40 miles apart.

In the first place there are many observers at work—scattered over the continent as postmasters, school teachers, &c.—whose records are sent in to the central bureaux. Some are telegraphed every day in time for the daily chart, others are chiefly used in drawing *average* maps. There are about 5,500 observers in all, but most of these are recording rain only, and send in their results once a month.

Here, however, is a map which shows where the weather stations are situated (see Fig. 1). A large proportion of West Australia has no stations, while the north of South Australia and Northern Territory are very poorly supplied. However, records are most useful where they affect most people—and in the most populous regions of Australia (as one can see) there are stations every ten or twenty miles. These enable us to record the weather results as accurately as necessary.

A. The Weather Chart in Winter

Let us consider a typical winter day such as 8 July, 1914. During the morning, stations all over Australia were telegraphing the condition of the weather at 9 a.m. (Since the sun shines first on Melbourne, and then on Adelaide, and much later on Perth, the observer has to take his records at 8 a.m. in Perth and 8.30 a.m. in Adelaide to keep time with the observer at 9 a.m. in Melbourne.) Let us consider first the wind direction (see Fig. 2). The arrows show clearly that the winds are blowing round a centre to the north-east of Kalgoorlie. We can also see that they tend to blow rather *outward from* the centre in each case, and that the whole stream of air is moving in a direction opposite to that of the hands of a clock—or *counter-clockwise*. This great eddy or whirl in the atmosphere is an anticyclone, but is usually known as a High, for reasons which will appear later.

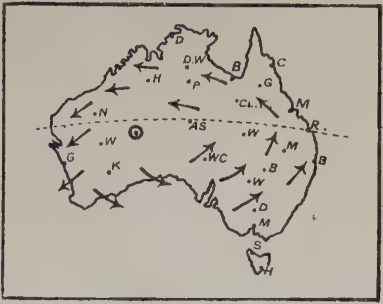

Fig. 2. General wind directions in anticyclone, 8 July, 1914.

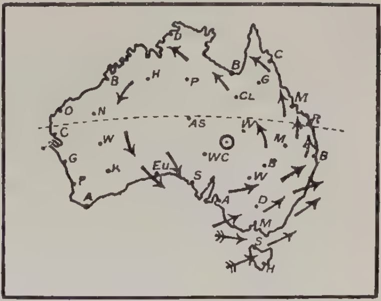

Fig. 3. General wind directions in anticyclone, 11 July, 1914.

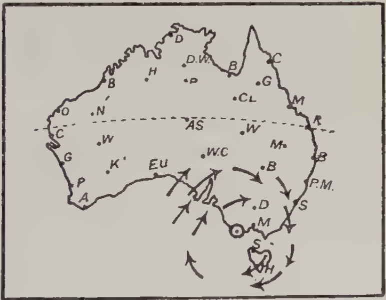

Fig. 4. General wind directions in cyclone, 7 July, 1914.

Now let us see what has happened in three days (see Fig. 3). Here is the wind chart for 11 July, 1914.[1] Much the same arrangement is present, but the centre is now just north of Lake Eyre. We now realize the important fact that these eddies move as a whole to the east, carrying with them the counter-clockwise rotation of the air composing them. (In the same way, in a river one often sees eddies circulating uniformly while they are being carried downstream.) If we measure this distance we find that it is about 1,000 miles. So that this High has a velocity to the east of over 300 miles a day, and this is a very usual speed for these disturbances to travel.

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[1] All the data on the weather maps (except rain) refer to 9 a.m. Melbourne time.

The very name would lead one to suppose that there is a complementary system to the High; and this is the case. Let us look at the wind chart for 7 July (see Fig. 4), just preceding the others sketched. In the south-east corner is an example of a cyclone, or, as it is often called, a Low. Unfortunately, much of this eddy lies over the water—where there are no stations. However, it is obviously a whirl, as is the High; but the winds composing it blow around in the opposite way, i. e. they move clockwise, or in the *same* way as the hands of a clock.

These two systems, the Highs and the Lows, are the chief factors which the meteorologist in Australia studies. Their variations give us (in these latitudes) rain and wind, heat and cold, drought and floods, and all the other changes which combine to form the weather.

The observers obtain the direction of the wind from the wind-vane at their station; but there is another record which they send in which tells us more accurately whether they are affected by a High or Low. This is the reading of the barometer, with which all the important stations are equipped. Most people think of the barometer as an instrument with a sort of clock-face with the words FINE, RAIN, CHANGE, &c., replacing the hours of the clock. This is the aneroid or *dry* barometer, whereas a meteorologist usually uses a mercury or '*wet*' barometer, of totally different appearance and construction.

Both these instruments inform the observer as to the weight of the atmosphere vertically above him. They only indirectly inform us as to the weather—and as the words on the aneroid-face refer usually to conditions at London, it is pure accident if they are applicable to localities in the colonies. Let us leave the discussion of the barometer to a later chapter and continue our study of the weather-chart.

The observers at all the chief stations telegraph to Melbourne, and to all the other capital cities, the readings on their barometers. These are plotted on a map of Australia, and at first glance seem to have no definite arrangement. We shall find, however, that all the figures lie between 29·5 and 30·3. If we connect up all the barometric readings of the same value we get a series of concentric curves of great interest (see Fig. 5). These curved lines are called isobars (from the Greek *isos* = equal), and they were first drawn so late as 1850. With their introduction the science of meteorology was first placed on a firm footing.

When we draw the isobars we see how closely the wind circulation agrees with the pressure distribution. In fact, air currents obey much the same laws as water, and in both cases there is always a movement away from regions of high pressure to regions of low pressure. The centre of the High is seen to have the highest pressure, so that the winds tend to blow away from this locality. It would be natural to assume that the winds would blow away *radially* from the region of highest pressure, but this is not quite what happens. In addition to moving away from the high pressure, these currents of air always have an even greater tendency to move to the left, and the combination of these two tendencies makes them take up a swirling instead of a radial motion. This left-hand tendency was first adequately explained by the American meteorologist Ferrel, and we shall discuss Ferrel's law later.

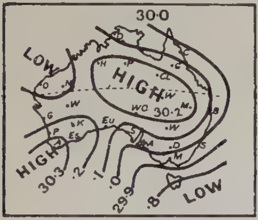

Fig. 5. General pressure distribution (isobars), 11 July, 1914.

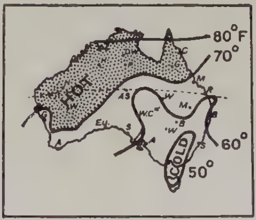

Fig. 6. General temperature distribution (isotherms), 11 July, 1914. Maximum for 24 hours preceding 9 a.m.

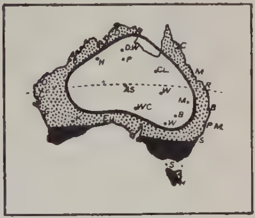

Fig. 7. Rain area for 24 hours before 9 a.m. 11 July, 1914, shown black. The dotted area was also cloudy at 9 a.m.

There remain several other records which are sent by the observer to the head office, and which are used in making the chart and in issuing the forecast. The most important is that of temperature. If the temperature records are written on the chart and lines drawn through all numbers of the same value, we get a set of curved lines called isotherms (*isos*, equal; *therme*, heat) (see Fig. 6).

If we plot the isotherms for 11 July we get a very interesting arrangement of the hot and cold areas. Normally, of course, we should expect the temperatures to decrease regularly as we approach the poles—which would give us isotherms parallel to the equator. But in this chart the west of Australia is hotter and the east cooler. Why is this? If we look at the wind chart we see that the east has southern winds, which bring air from the Antarctic seas, while the western area is affected by northern winds, which blow from warm regions and so raise the temperature. Hence the east side of a High (known as its front, since it moves bodily to the east) is generally cool, and the west side (the rear) is generally hot. This is one of the simplest pieces of forecast 'magic', which any one can perform from the daily chart.

The cool loops in the 60° isotherm in the south-east are due chiefly to topographic factors, and their discussion must be postponed.

Each morning at 9 a.m. the observer visits his rain-gauge and enters in his book the depth of rain which has fallen in the past twenty-four hours. These figures are also telegraphed to the office, and are usually plotted on the daily chart, though not by lines of equal rainfall (*isohyets*).

Each patch of country where rain has fallen is shown on the official map by a ruling of close lines. These patches are known as Rain Smears, and the study of their relation to the winds, temperatures, and pressures is perhaps the most important in Australian meteorology.

In the chart for 11 July there are three rain smears (shown as black areas), all in the south (see Fig. 7). Comparing this map with the one for the winds, we see that in each case the rains have fallen where winds from the south have carried moist air from the sea on to the land. This is the commonest type of rainfall, though there are many other types, which will be referred to in due course.

The last of the maps (Fig. 7) dealing with the weather of 11 July also shows the area where the skies were definitely cloudy. This also is not haphazard, but is related to the High in a very definite manner. In fact, the central portions of a High are nearly always clear, while the clouds congregate all round the margins, especially in the south-east.

If we look more carefully at the chart of the winds we shall see that some of the arrows have several 'feathers', while others have none (see Fig. 3). The former, denoting strong winds, are to be found chiefly on the southern and eastern margins; the light winds occur in the central area.

To recapitulate what we have learnt so far. In July Australian weather is often dominated by an anticyclone (or system of high pressure), which occupies an area somewhat less than that of the continent. This system moves eastward at about 300 miles a day. The centre line or track of the High lies approximately over Kalgoorlie and Oodnadatta—in other words, it keeps near latitude 27° S. The winds blow around the centre in a counter-clockwise direction and somewhat away from the centre. They are strongest in the south and east. In the centre of the High the winds are slight. Here also the sky is generally cloudless, and of course no rain falls. The clouds usually border the area of high pressure, and the rainfall is chiefly along the south coast. The cool south winds of the front of the High and the warm rear winds lead to a warping of the isotherms in agreement.

B. In Summer

We will now consider the same set of conditions for midsummer. On 6 January, 1913, the wind circulation is in the nature of an eddy revolving around Halls Creek in northern West Australia (see Fig. 8). The winds are clockwise, so that we have to do with a cyclone, or system of low pressure. Here the winds are blowing rather obliquely toward the centre. If we plot the isobars we find in addition that a well-marked High lies over the Bight, with its centre (as near as we can judge) south of Esperance. Another is just leaving New South Wales in the far east (see Fig. 9).

The rains for the past twenty-four hours are confined to the north in this example (Fig. 13). This is generally the case in summer, though they are here more abundant than usual. Instead of lumping all the rain into a twenty-four hour ‘smear’, let us see where rain was actually falling when the other observations were made, i. e. at 9 a.m. This is shown in Fig. 10, and tells us that the front (east) of a Low where the wind seems to change in direction (from north to south-east) is a very favourable locality for rain.

In the next two charts the same relative position is indicated (see Figs. 11 and 12). As the Low moves east, so the falling rain moves east. These ‘bands’ or ‘splashes’ overlap, and added together give the broad smear which is usually shown on the weather chart, and which appears in Fig. 13. Other influences less directly connected with the Low have also given rise to rain on this occasion. It is rarely that a cyclone in the north of Australia moves so regularly as in this example. Usually their paths are very erratic, but it is as well to start with a simple type.

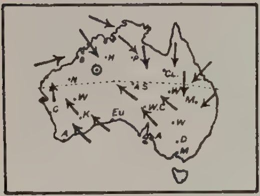

Fig. 8. General wind directions in cyclone, 6 January, 1913.

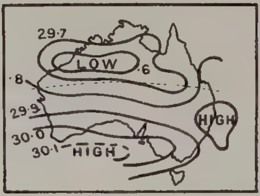

Fig. 9. General pressure distribution (isobars), 6 January, 1913.

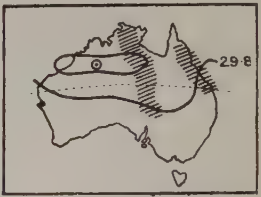

Fig. 10. Rain actually falling at 9 a.m. 6 January, 1913.

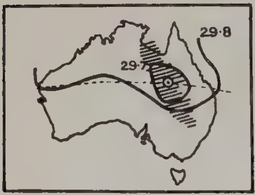

Fig. 11.

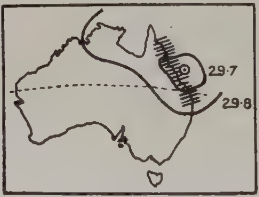

Fig. 12.

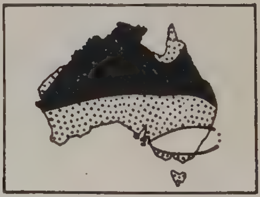

Fig. 13.

Fig. 11. Rain falling 9 a.m. 7 January, 1913. Fig. 12. Rain falling 9 a.m. 8 January, 1913. Fig. 13. General distribution of the rain in 24 hours before 9 a.m. 8 January, 1913. The dotted area was also cloudy at 9 a.m.

The temperature chart is very striking, and illustrates the properties of the wind eddies well (Fig. 14). Dubbo in New South Wales had a temperature of 90°, while Laverton—really farther north and farther from the cool ocean—had only 58°. So that the isotherm for 90° is S-shaped, showing a cold bulge running into it in the west, and a hot bulge pressing it down in the east. (In this map the *maximum* temperatures for the past twenty-four hours are charted.)

The rear of the High (off Sydney) gives hot winds, and so does the front of the Low in the north. The front of the High in the Bight gives cool winds, which are drawn up towards the Low over West Australia.

These conditions are general. 'Heat waves' nearly always occur in the intermediate area behind the High and before a Low; 'cold snaps' occur behind a Low and before the following High.

The distribution of cloud was remarkable, as shown in Fig. 13. Practically the whole of Australia, except the Murray Basin, was cloudy on this date. This is most unusual, but will serve to remind us that low-pressure are cloudier than high-pressure areas. The clear area lies over the *col* (or neck) between the two anticyclones, where there is often a descent of dry air.

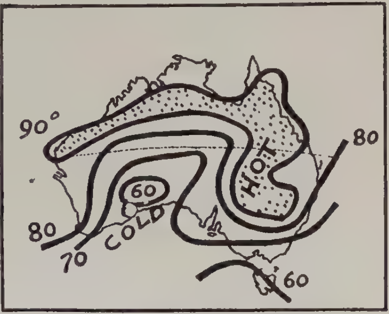

Fig. 14. General distribution of temperature (isotherms), 6 January, 1913. Maximum for 24 hours preceding 9 a.m.

Perhaps the most important conclusion to be drawn from these charts is one to which attention is now directed. We saw that in July the path of the centres of the Highs was along latitude 27° S. In January, on the other hand, the centres of the Highs are well south of the continent, and may be taken as lying near latitude 37° S. If we were to plot the paths of the centres of the Highs in other months of the year, we should find that the average track of the Highs gradually moved north during autumn and south during spring between these extremes. Obviously the controlling factor is the sun, which also appears to move between the tropic of Cancer (21 June) and the tropic of Capricorn (21 December) every six months.

The variations in climate and weather induced by the swing of the sun form the subject of a later chapter.

CHAPTER III

WORK AT A SMALL STATION

A. Barometers

Let us now leave the central office and visit one of the numerous 'Third order' stations to see how the records are collected by the observer. One of these stations is usually equipped with half-a-dozen instruments. Of these the chief are a barometer, to record pressure, and four types of thermometer. The latter comprise a maximum thermometer, a minimum thermometer, a dry-bulb thermometer, and a wet-bulb thermometer, the two latter forming a pair. These thermometers are placed within a special wooden cupboard called a screen.[1] There is also a rain-gauge and usually a wind-vane.

The Pressure of the Air. The most important instrument is undoubtedly the barometer, and its principles are less understood than those of many other instruments, for the reason that variations in atmospheric pressure do not directly affect the human senses. And yet the essentials can easily be grasped.

In the first place air has weight, but unlike the weight of solids or liquids it depends fundamentally on the pressure to which it is subjected. A cubic foot of air weighs 573·5 grains under ordinary conditions, or, about 13 cubic feet weigh one pound.

In metric measures one cubic centimetre of pure dry air (at 0° Centigrade and 760 millimetres pressure) has a mass of 0·0012927 gram.

If all the air in the atmosphere were compressed until it contained the same number of molecules in each cubic foot as it does normally at sea level, then this shell of atmosphere would be about five miles thick.

Many observations show us that the atmosphere, however, extends in a diffused form much farther from the earth's surface than this. We may safely assume, from the friction experienced by meteors, that there is some air at a distance of 180 miles; but at $6\frac{1}{2}$ miles man has to have recourse to artificial supplies, as was shown by the balloonist Dr. Berson in 1901.

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[1] Described on page 27.

Suppose now that we have an elastic vessel, such as a toy balloon, just containing a cubic foot of air at sea level. If we carry this up a mountain we shall see that the balloon gradually expands until at about 18,000 feet it will contain just double the volume, or two cubic feet, though the number of molecules remains the same. At this height the pressure of the atmosphere is halved—or, there is as much air in the narrow zone beneath us as in all the tremendous space above our level.

The pressure of the air is really due to the total effect of a bombardment of the gaseous molecules of which the air is composed. If they are confined in smaller volumes (as is the case near the earth) there are more blows per second (i.e. more pressure) on a given surface than if the molecules are less crowded, as at higher elevations.

We have now learned that the pressure of the air depends on the height of the observer. So that we must know the height of our station quite accurately with regard to the standard surface of mean sea level. But the pressure varies (up to 3 per cent.) from day to day with the movement of Highs and Lows, as we have seen in the preceding chapter. It is this change with which the barometer is primarily concerned.

The pressure at sea level is about 15 lb. to the square inch, and though this is a large amount it is not noticeable, because the air exerts its pressure in every direction and penetrates inside as well as outside most bodies. But what happens when we exhaust the air from a bladder? The sides collapse; not from suction as one usually hears, but because the air is pressing on the *outside* only, and so squeezes the walls together. If the vessel can resist this pressure, no such deformation occurs.

A famous experiment performed at Magdeburg about 1650 well illustrates this pressure. Two copper hemispheres (about a yard in diameter, and provided with flanges) were placed rim to rim. On exhausting the air inside the sphere, two teams of horses pulling in opposition could not separate the hemispheres.

Now let us see what is the construction of a barometer. We can grasp the principle best by a simple experiment, where water takes the place of air (see Fig. 15).

We take a glass cylinder about 18 inches deep and, say, 6 inches across. Into this we pour 2 inches of mercury. Then insert a test-tube of about 1-inch diameter, so that it stands inverted in the mercury. The mercury remains at the same level (*a*), within and without the tube.

Now pour in 12 inches of water into the outer cylinder ; it rises to *c*. The pressure of the water forces the mercury up into the test-tube to (*b*), a height of about 1 inch. The relation is

$$\frac{\text{ab}}{\text{ac}} = \frac{\text{specific gravity of water}}{\text{specific gravity of mercury}};$$

for we may neglect the effect of the slight amount of air imprisoned in the test-tube, though we must not push the analogy too far.

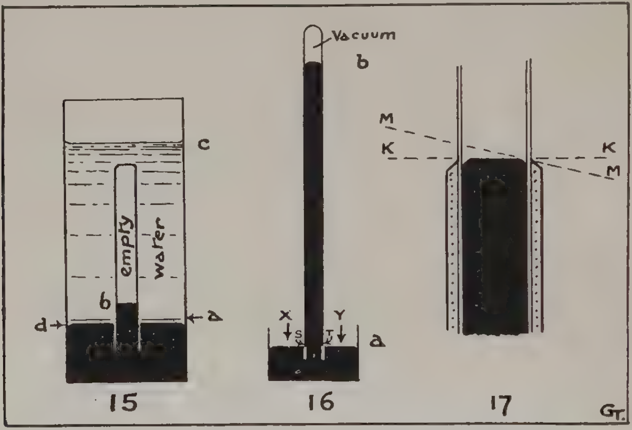


FIG. 15. Experiment (using water) to illustrate the pressure of the atmosphere on the mercury.
FIG. 16. The simple mercury barometer. The distance *a b* is measured.
FIG. 17. The movable sighting edges (dotted) which prevent parallax.

If we add more water, the mercury rises in the test-tube. If we remove some water its pressure decreases and the mercury falls. Exactly the same effects take place when the layer of air above the cistern of the barometer varies in weight.

The barometer in its simplest form is a glass tube about a yard long, which is sealed at the top and open below. This is usually standing inverted in a shallow dish of mercury, and when in use the mercury is filling most of the long tube—apparently in defiance of gravity (see Fig. 16).

We have now to consider what forces are acting at two levels of the mercury—at *a* in the dish, and at *b* about 30 inches above it. To understand these forces we should see the instrument set up. The tube is first completely filled with mercury and then inverted (as shown in Fig. 16) with the tube opening beneath the mercury. The mercury drops to the position shown at *b*—and above this lies an empty space, called (after the discoverer) the Torricellian Vacuum.

[If we bore a hole through the glass at *b*, the column of mercury immediately drops, and both within and without the tube it lies at the same level.]

Now at X and Y (in Fig. 16) we have 15 lb. per square inch pressing down on the mercury. At *b* we have no pressure at all. At S T (at the foot of the column) we have the pressure of the column of mercury. If the cross-section of the tube is 1 square inch, we shall find that the column of mercury weighs just 15 lb. Hence it balances. If the column is narrower, then the air pressure (transmitted from the air through the mercury in the dish) acting on it is less ; and the weight of mercury balanced will be proportionately less also.

As the air pressure increases at X and Y, it forces more mercury up into the tube, and the 'barometer rises'; as the pressure decreases (for instance, when a cyclone or Low approaches) the column of mercury responds and the 'barometer falls'. The principle is just the same as explained in Fig. 15.

Why use mercury ? Simply because it is convenient ; it does not evaporate, and it takes up little room. But other liquids serve quite well. In the *Times* Office was an instrument where glycerine was used. In the birthplace of Torricelli (in Italy) oil is used, and there the barometer is nearly 37 feet high.

In almost every farm in Australia is a crude barometer, about 30 feet long, where water is used as the liquid. For the 'lift' of an ordinary pump varies with the pressure of the atmosphere, though the apparatus is too crude to show this effect readily.

If we compare all these substances, air, oil, water, glycerine, and mercury, we find that the lengths of the columns concerned vary as their densities. Thus 5 miles of air is equivalent to 37 feet of oil, or 33 feet of water, or 28 feet of glycerine, or 30 inches of mercury. If we weigh the columns (giving each a cross-section of 1 square inch) we shall find that all of them have the same weight of about 15 lb. In the experiment in Fig. 15, if we increased our column of water to 33 feet, we should find it would balance 30 inches of mercury.

Mercury Barometers

There are four types of barometer which are in common use. Two, the Kew and Fortin types, use mercury ; and two are dry barometers, or aneroids. Probably the Kew barometer is the one most widely used as a standard instrument ; but the Fortin is the simplest instrument, and we shall consider it first.

The distance in the mercury barometer which we wish to measure exactly is that between the two mercury surfaces (*a b* in Fig. 16). This might seem a simple operation, but it needs care, and must be done according to standard methods.

For instance, the mercury does not stand level in the tube, but a curved surface (meniscus) is formed, which is higher in the middle. The latter (highest portion) is the level we use. Unless we are careful we shall not read the scale-division just level with this mercury surface, but owing to the eye being too high or too low (M M in Fig. 17) we get an error of parallax. To prevent this the small sighting straight-edges before and behind the mercury surfaces are employed (see Fig. 17). The two edges are moved together, of course.

Secondly, when the level of the mercury in the cistern falls, the zero (or beginning) of the scale is of course lower (see Fig. 20) ; and is now farther from any given figure engraved on the scale (say 30 inches) than when the atmospheric pressure is lower (when of course the mercury *in the cistern* rises). This will be clearly understood from Fig. 20. [It is usual for the scale on the barometer to be fixed permanently to the tube.]

To overcome this variation in the zero level, the cistern of the Fortin barometer has the base made of leather, which can be raised by a central screw so as to lift the mercury in the cistern (see Fig. 18). Above the mercury is a small ivory point, and this is the permanent zero of the scale.

At each reading the mercury in the cistern is adjusted by the screw until it just touches the ivory point. This is only equivalent to pouring a little more mercury into the cistern and cannot affect the distance x y between the two levels which we wish to measure (see Fig. 19).

This is an operation which often puzzles beginners, so that the annexed sketch may help them (Fig. 19). The distance $x\,y$ is the same in both barometers, though the vacuum (above x) may be *any* convenient length. Obviously if the scale is engraved *on the tube* it is necessary to have the mercury always brought to the same zero, or the readings can never be comparable.

There is, however, another method in use in the *Kew* barometer. Here the capacity of the cistern is kept constant, but the scale is altered. Hence the distances between the inch-marks are not standard inches, but represent what a Fortin would indicate at the respective pressures.

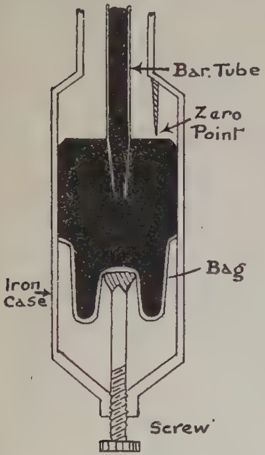
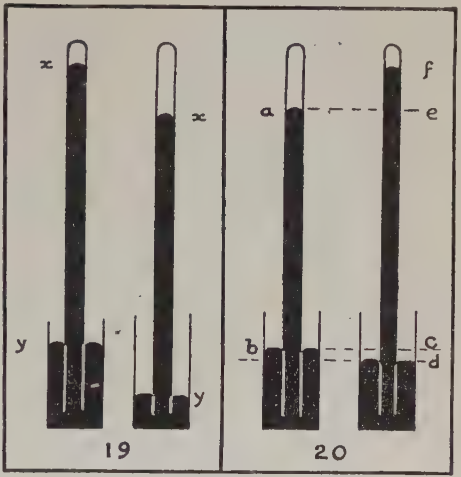


Fig. 18. The Fortin Barometer. A section through the mercury cistern showing the leather bag and the zero point of the scale.



Figs. 19 and 20.

In the sketch (Fig. 20) a represents the reading with low pressure conditions, where $a\,b$ is, say, 29 inches. Now let the air pressure rise to 30 inches; and we see that while the mercury in the tube has risen from e to f, in the cistern it has fallen from c to d. Obviously $f\,d$ is 30 inches; and $ef + c\,d =$ one inch, so that ef is *less* than one inch. But in the Kew pattern f is *labelled* 30 inches, and so with the other divisions. No harm is done provided the conditions remain as when the scale of the instrument was attached to it.

Barometer Corrections. There are, however, other, less fundamental, but important considerations, connected with reading a barometer. For instance, when mercury is warmed it expands—as do most substances. As we are measuring a length (and not a weight of mercury) it is necessary to watch this point.

Every good barometer has a small thermometer attached to it; for on a hot day an inch of mercury in the tube will weigh less than on a cold day. So that if the air pressure is shown by the barometer to rise an inch on a *hot* day, on a *cold* day more pressure will be needed to raise the mercury through the same distance; for the mercury is heavier as stated.

The glass of the barometer also expands slightly, and so does the brass scale. The mercury expansion is the largest, but all three are taken into consideration in tables issued with the barometer. The reading at freezing-point (32° Fahrenheit) is made the standard, and has of course no correction. These varying amounts must be subtracted from the reading at higher temperatures. Thus about 0·1 ($\frac{1}{10}$) inch is subtracted near a temperature of 70°, and 0·15 near a temperature of 90°. (It naturally differs slightly with the length of the column of mercury; the correction being 0·173 at 90° if the column is 31 inches long; and 0·150 if it is 27 inches long at 90°.)

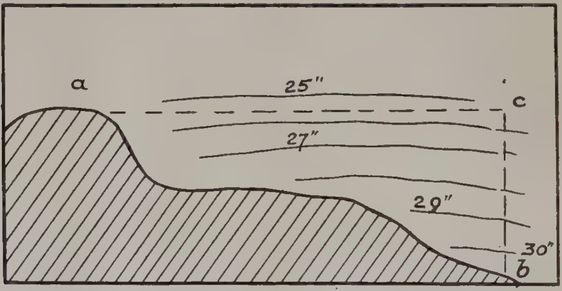


FIG. 21. Reduction of barometer reading to sea level.

Another correction is due to the *elevation* of the station. We plot the pressure on the daily chart so as to see where movements of the atmosphere are likely to take place. Consider two stations Fig. 21, *b* at sea level and *a* at 7,000 feet elevation. (Such a pair would be Bega and Kosciusko.) Suppose the barometer at *b* shows a pressure of 30·0 inches, and that at *a* a pressure of 25·0 inches. If these were plotted directly on the chart we should have a tremendous gradient (i. e. very crowded isobars), and would naturally expect great gales.

The diagram shows that *a* is really comparable with *c* (at its own level) and not with *b*; just as it would be if we were dealing with water pressures. Hence, to obtain comparable figures we must reduce them to one standard—that of sea level. If now the value 25·0 inches be reduced to the value at sea level by suitable tables (furnished to the observer), it will give a figure close to 30·0 inches. We realize, therefore, that there is nothing abnormal in two near barometers having such different values, if they are at different elevations.

We know that the earth is not spherical, but is flattened at the poles. Hence places on the equator are farther from the centre of the earth than they are at the poles. This means that the pull of gravity differs slightly with the latitude; and latitude 45° has been chosen as a standard.

A mass of mercury which exerts a force of 15 lb. to the square inch in latitude 45° has less weight when taken to latitude 34°; and so 15 lb. pressure will raise it higher at 34°. The converse applies if it be carried nearer the poles. Thus for latitude 34° S. (near Sydney) this correction is about 0·029 inch, which must be *subtracted*, so that atmospheric pressures shall be of the same value. At Ross Island, Antarctica, we used a correction of about 0·07 inch, which was *added* to the reading of the barometer. The whole difficulty is due to the fact that the *weight* of a body is a *variable*, depending on its distance from the centre of the earth; though the *mass* of the body (i.e. the total number of molecules in it) remains the same.

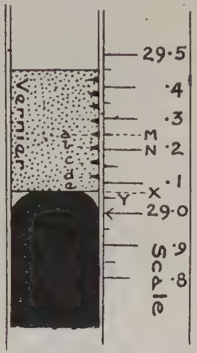


FIG. 22. The vernier attached to the mercury barometer. It is a movable scale and is shown dotted, while the mercury is black. The reading is 29·058 inches. The vernier usually shows 25 divisions, numbered 0 to 5.

A principle of measurement which often puzzles beginners is that involved in the *vernier*. By means of an attached scale, whose divisions differ very slightly from those of the main scale, a much more accurate reading can be attained with great ease. The vernier in the standard barometer is usually so graduated that each vernier division is $\frac{1}{25}$ *shorter* than each scale division. The scale divisions are 0·05 inch apart. Therefore the vernier divisions are $\frac{24}{25}$ of this length, or are 0·002 inch shorter.

The zero of the *movable* vernier is brought to the exact level of the top of the mercury in the barometer. In the sketch (Fig. 22) this is marked *e*. On the main scale the reading is obviously just over 29·05 inches (Y), and we want to measure the distance XY. Looking now along the vernier scale we see that the fourth vernier division (at *a*) coincides with some line on the long scale (29·25 in this case, but we need not read this).

Now we know that *a b* is 0·002 inch shorter than MN, and *a e* is four times *a b*, and therefore 0·008 inch shorter than MY (four divisions on the long scale). Hence XY = 4 × 0·002 = 0·008. The true reading of the barometer is therefore 29·05 + 0·008 = 29·058 inches.

THE ANEROID AND WEATHER GLASS

The aneroid barometer consists of a small disk-like drum of corrugated metal, which is practically exhausted of air. It is usually 2 or 3 inches in diameter. The upper and lower faces are kept apart by strong steel **C** springs. The pressure of the external air—forcing these two faces together—acts against these springs. The varying pressure gives rise to a movement of one face of the disk (as the other is fixed); and this movement is magnified enormously (by various levers), so that it can readily be measured by the large movement of the pointer (see Fig. 25).

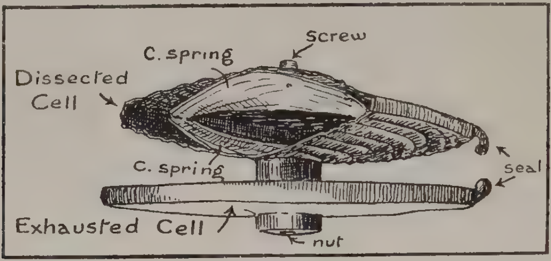


FIG. 23. Two aneroid cells from a barograph. The upper one is cut open (and one-third removed) to show the springs which force the upper and lower faces apart against the pressure of the air.

Aneroids are not very reliable, because the metals involved gradually become 'tired', and do not quickly return to the same points, when the instruments have been in use for considerable periods.

They are largely used, however, to determine the relative heights of two places, because they are very portable. In these measurements we usually assume that the atmospheric pressure has not changed materially between the two observations. Hence no great interval of time should elapse between the reading at the base and at the summit of the journey. It is better to read the instrument several times to see that the pointer has taken up a final position. For accurate work a second aneroid should be used at the base, for comparison.

An aneroid barometer should be frequently compared with a standard mercury barometer. It is then a very valuable instrument for use on journeys, where the other type would be generally too cumbrous and fragile.

The imposing weather glass is really an aneroid with a cheap-jack face. For climates controlled by the same range of elements as England, the words Rain, Change, Fair have some value. But if the English instrument be transferred to other latitudes, these directions can only be misleading.

Let us compare the monthly pressures in London, Brisbane, and Melbourne. We shall see that not only are the pressures quite different in similar seasons, but the extremes are very different also.

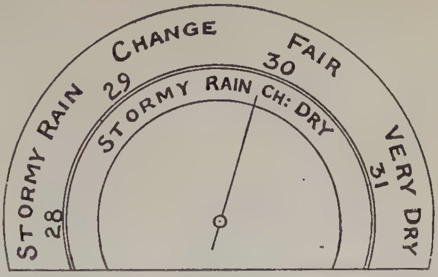


Fig. 24. The 'Weather Glass' dial. The outer names apply to London, the inner names to Melbourne. Neither are particularly useful.

		London.		*Brisbane.*	*Melbourne.*
Spring	March . .	29·93	September .	30·07	29·99
	April . .	·95	October .	·04	·96
	May . .	·98	November .	·00	·95
Summer	June . .	30·01	December .	29·92	·89
	July . .	29·98	January .	·89	·91
	August .	·98	February .	·92	·96
Autumn	September .	·98	March .	·98	30·03
	October .	·91	April . .	30·08	·10
	November .	·94	May . .	·13	·10
Winter	December .	·97	June . .	·10	·07
	January .	29·99	July . .	·10	·09
	February .	30·01	August .	·13	·06

Perhaps the chief point to notice is the remarkable difference between the range of pressure in the British Isles and in Australia. In 1884 in Perthshire 27·4 inches was recorded, and in 1896 31·1 inches. In Australia the barometer rarely falls below 28·6 and does not rise above 30·7.

The stereotyped legend on the face of an English weather glass, when transferred to Australia, implies that in the latter place we never have *stormy* or *very dry* weather! (see Fig. 24).

If it be thought worth while to label the pressures—which is doubtful—then the inner arrangement (shown above) is certainly better suited for conditions in the south of Australia.

The Barograph

The principles of a continuous recording instrument can be readily grasped if an ordinary barograph be examined. This usually consists of an aneroid connected to a pen, which records on a rotating cylinder carrying a sheet of paper.

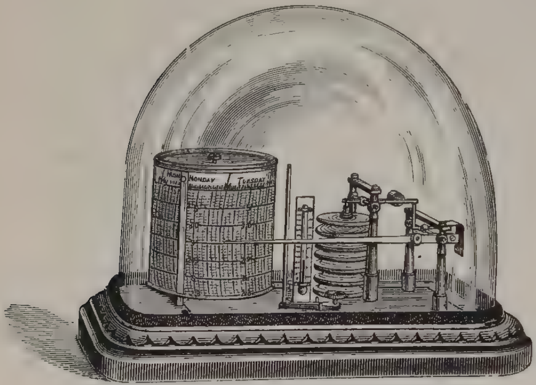


Fig. 25. Self-recording barograph.

The aneroid is often compound, consisting of a battery of several drums connected together. This magnifies the movement due to the variation of air pressure. The levers and the pen are quite simple in construction, and hardly need explanation.

The chronograph—or recording apparatus—consists of a clock inside a drum. Instead of the clock-case being stationary and the central axis rotating (as in a timepiece), the axis is fixed and the clock-case rotates. The latter carries a sheet of paper ruled in squares to show time and pressure.

The clock usually rotates once every twenty-four hours, and this determines the twenty-four vertical divisions on the chart. The maximum movements of the pen—according to the pressure on the aneroid drums—determine the limits of the horizontal lines on the chart. Thus for Australia the chart would need to show from 31 inches to 28 inches for sea-level stations.

This instrument also needs comparing with the standard barometer at regular intervals. With this precaution it gives very valuable records.

In the first-class stations there are sometimes recording barographs where mercury is the agent employed to detect pressure changes. Electrical connexions are often made use of, but these instruments are expensive, and need great care in taking observations. They are never furnished to less important stations.

The new Unit of Pressure—the Millibar

The pressure of the atmosphere is of the nature of a force, and we are told in physics that

Unit of Force = Unit of mass × Unit of acceleration.

There is obviously no authority here for the use of *inches* as units of measurement in the mercury barometer; while in the aneroid the graduation in *inches* is particularly absurd, since no lengths are involved. In the metric system the unit of force is the dyne (from the Greek 'dynamis' = force). Suppose a mass of one gram to be moving at a certain velocity; if this velocity be increased (by the use of force) at the rate of one centimetre per second, the latter increase is its acceleration—and the force required to give this unit of acceleration is our unit of force, the *dyne*.

One might imagine that it would suffice to use the dyne as our unit for atmospheric pressure; but just as it is convenient to use pence, although the sovereign is the standard, so the dyne is not always a handy unit. It is, however, a long way to the *millibar*—which is the unit to which I propose to introduce the reader.

For many years the scientific standard in connexion with barometers has been defined as the pressure of a column of mercury 760 millimetres high at sea level and a temperature of 0°C. in latitude 45°. This is called the standard atmosphere. When converted into the above metric units it amounts to 1,013 dynes per square centimetre.

This is the same as 1·013 megadynes, since 1,000 dynes equal one megadyne.

The practical unit of atmospheric pressure is a little less than one 'standard atmosphere'. It is in fact defined as one megadyne. Since the barometric pressure falls as we rise above sea level, we shall obviously soon come to the level where the megadyne holds sway. As a matter of fact, for standard conditions it is 348 feet above sea level. Here the barometer stands at 29·53 inches, or 750·1 millimetres, and the column of mercury exerts a force of one megadyne, known conveniently as a *Bar*. One-thousandth of this force is the Millibar.

We can get a mental picture of a millibar by saying that the force exerted by a pressure of *one inch* of mercury is 33·86 millibars (when the other standard conditions are complied with). But it is quite incorrect to say that one inch *equals* 33·86 millibars.

B. Thermometers

The various thermometers in use at a small station are much more readily understood than is the mercurial barometer. Almost all liquids expand on being heated, so that, as in the barometer, several liquids can be used in thermometers. Mercury and alcohol are, however, the only fluids in common use.

There are also thermometers based on the expansion of metals with heat, which might equally well be termed ‘ aneroid ’, but the term has luckily never come into vogue.

The chief difficulty with thermometers consists in the various scales in common use. The melting-point of ice is usually adopted as one datum, and the boiling-point of water as the other. These two degrees of temperature were called 0 and 100 by Celsius, who devised the Centigrade thermometer.

Fahrenheit took the same critical points, but divided the scale into 180 degrees. He did not, however, make the lower datum his zero, but apparently fixed the zero at the lowest temperature at his command. This was obtained by mixing snow and salt. He found that if the fluid expanded through 180 divisions during the change from the melting of ice to the boiling of water, it expanded through 32 such divisions in passing from the temperature of his snow-salt mixture to the melting-point of ice. Hence 32° F. and 0° C. mark the same temperature, while 212° F. and 100° C. are equivalent. It follows that a Fahrenheit degree is only 100/180 (or five-ninths) of a Centigrade degree.

Both of these systems are very artificial. There is in fact an advantage in the much-abused Fahrenheit, in that *negative* temperatures are not usually recorded in our log-books. There is no special advantage in the Centigrade scale, though many people erroneously think it offers similar facilities to the decimal systems in weight and coinage.

The Absolute Scale

Just as in the barometer scales there is no doubt that we must ultimately replace ‘inches ’ by ‘ millibars ’, so in thermometers both the above scales are giving way to the ‘absolute ’ scale. This depends on the law that gases (under constant pressure) expand uniformly with increase of temperature. If we use the Centigrade division as a unit, we find that the gas increases by 1/273 of its volume at 0° C. for each increase in temperature of one degree Centigrade. Its volume obviously decreases by 1/273 as the temperature is lowered one degree. Carrying this process down the scale, we find that at − 71° C. (the lowest temperature recorded in Polar regions) the gas has lost one quarter of its bulk, and logically at −273° C. it should lose all of its bulk ! Obviously this cannot happen, but undoubtedly at that temperature a gas would have lost its molecular energy and would be inert.

This datum of −273 C° is a perfectly definite zero quite independent of the kind of gas whose expansion is measured. Hence a scale measured from this zero is called the *absolute scale.* As a matter of convenience, Centigrade divisions have been adopted for the scale, and thus 0° C. is the same as 273° A. or + 32° F. ; and 100° C. = 373° A. = 212° F. In certain thermometers issued by the London Office this graduation is adopted already. It has a logical zero; it is extremely convenient in all calculations involving the volume and temperature of the air; and obviously no negative figures can ever be recorded, for it starts at bed-rock.

In recording temperatures we must realize what is really required. There are many temperatures obtainable, depending on the surroundings of the thermometer, and for purposes of comparison we must have similar conditions in all cases. The temperature which is chiefly required is that of the free air 4 feet above the ground and shaded from the sun in a louvred cupboard, called the Stevenson screen (see Fig. 188).

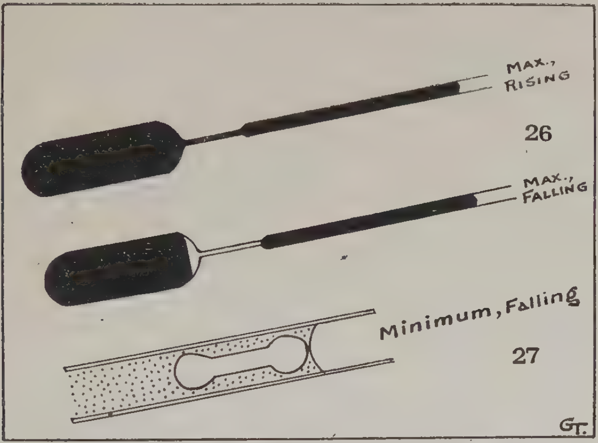


Fig. 26. Maximum thermometer, showing the constriction filled when rising, but empty when falling. (Diagrammatic.)
Fig. 27. Minimum thermometer, showing the index pushed down by the meniscus of the alcohol (dotted). (Diagrammatic.)

If we expose the thermometer to the sun we do not obtain the *air* temperature by any means. For instance, 154° F. is undoubtedly hot; yet this was recorded in Antarctica in 1902! But the true *free-air* temperature at this locality was +24° F., or *eight degrees below freezing!*

Maximum and Minimum Thermometers

The above instrument, of course, only shows the temperature at the time of observation. It is often necessary to know the maximum and minimum temperatures during the preceding twenty-four hours. Two special thermometers are provided whose action is quite easily understood.

The principle in the ordinary maximum thermometer is that the force of *expansion* in mercury is much greater than the force of *cohesion*. There is a contraction in the bore of the thermometer, close above the bulb, so that the mercury thread is here so slender as to be barely visible (see Fig. 26).

When the temperature rises, every small portion of mercury expands, and the increase of volume makes the mercury move up from the bulb through the constricted portion of the tube.

When the temperature falls the mercury contracts. Cohesion of the molecules tends to keep them together, but the resistance offered by the constriction readily overcomes this slight bond. So the thread of mercury breaks at the constriction, and the mass of mercury in the bulb contracts independently of that in the bore. The thread of mercury therefore remains in the position reached at its farthest expansion.

The maximum thermometer registers only the maximum temperature. When removed and jerked sharply with the bulb down, the mercury readily passes through the constriction and unites with the rest in the bulb. When this has been done the 'max.' should read the same as the ordinary thermometer. The maximum usually occurs about 2.30 p.m., but under special conditions the temperature may fall throughout the day, when the maximum occurs in the early morning.

In the minimum thermometer another force comes into play. The fluid used is usually alcohol, which allows a small glass index to be seen. This index is shaped like a dumb-bell. It is brought to the top of the spirit when the instrument is 'set' (by inverting the latter), and later as the spirit contracts the float is dragged down with it.

The upper boundary of the spirit forms a peculiar surface—concave upwards—which depends on the surface tension, and is called the *meniscus*. Surface tension causes this meniscus to act somewhat as if it were an elastic membrane, and as the spirit contracts it pushes the dumb-bell towards the bulb.

When the temperature begins to increase, the meniscus moves up the bore. It exerts no more 'pull' on the float than an elastic membrane would, and consequently the float remains at the lowest point reached. This thermometer is placed almost horizontal, so that gravity does not cause the float to sink too far.

The other types of thermometer—not usually used at a small weather station—are described in detail in later sections.

CHAPTER IV

COMPOSITION, HEIGHT, AND VARIATION IN THE ATMOSPHERE

All matter belongs to one of three states of being: it is solid, liquid, or gaseous. Each of these 'states' is represented in one of the three great divisions into which our world can be divided. The solid sphere on which we walk is conveniently termed the lithosphere, the liquid envelope occupying the great hollows in the earth's crust is termed the hydrosphere, the outer envelope or shell of air is the atmosphere.

We may note that the lithosphere in the form of mountains and oceanic deeps projects irregularly on both sides of the general level. Its form is very definite, and within limits is rigid. The chief feature of the hydrosphere is its definite upper surface, which is approximately level, but is highly mobile. The atmosphere is characterized by much greater mobility, and by the fact that this gaseous envelope has no definite upper surface.

It is of course with the outer envelope—the atmosphere—that the science of meteorology is essentially concerned. The atmosphere consists of a mixture of many gases, of which only four or five are of any importance from our point of view. These are nitrogen, oxygen, argon, carbon dioxide, and water vapour.

Priestley first separated the chief constituents and showed that the most important element consisted of oxygen—which forms 23·2 *per cent.* by weight. This he showed to be diluted by 76·5 per cent. of nitrogen, which is almost the most inert of gases. In 1894 about one per cent. of the air (formerly grouped with the nitrogen) was found to consist of another gas named argon. But for all meteorological purposes it may be grouped with the nitrogen which it so closely resembles.

Oxygen is the most important of these gases, for it is to the chemical transformation when the oxygen in our lungs combines with the carbon in our bodies that all our energy is due. As a result of animal respiration much carbon dioxide is given to the air. This, however, is absorbed by plants, so that a balance is maintained by the animals and plants whereby the composition of the atmosphere does not change appreciably.

Carbon dioxide is slightly variable. It is more abundant in towns and similar places, where carbon in the form of protoplasm in living organisms is being slowly oxidized ; or in the form of coal, wood, &c., is being more rapidly oxidized (i. e. burnt). It usually forms 0·05 per cent. by weight, and never exists to a dangerous amount even in a crowded living-room. It has been suggested that it was much more abundant in past geological time, and it may have been a factor in causing the great variations in climate which the earth has experienced in earlier epochs.

Water vapour obviously varies greatly in amount with every change of the weather. Since rain, snow, hail, clouds, mist, and dew are all but various forms of water, it is evident that meteorology is largely made up of a consideration of the part played by water in the atmosphere. It may increase in quantity until it reaches 4 per cent., or diminish in dry, cold, desert regions to an extremely small proportion.

The variation of the *invisible* amount of water vapour in the air will be considered when we discuss the humidity of the air. It is not too early to mention that the changes of state of water from vapour to liquid may be accompanied by the production of a great deal of heat energy; and to this, as we shall see, is largely due the violence of the tornado and the hurricane.

Dust

There is one constituent of the atmosphere which is quite distinct from the gases enumerated above, and that is dust. This consists largely of fine sand, soot, bacteria, salt, &c., in the *lower* layers ; while in the *upper* layers it is chiefly composed of volcanic dust and of fine meteoritic fragments from beyond the earth.

It has both good and evil effects. Among the latter belong the damage due to dust in houses, and to many diseases, such as influenza, which often follow dust storms. *Per contra* are the wonderful colours at sunrise and sunset ; while twilight is largely due to the sun's light being reflected from high-level particles, which can catch his beams long after the surface has lost his light.

We shall see that the presence of dust in the upper air probably leads to an appreciable warming of those layers of the atmosphere, while it is thought that great outbursts of volcanic dust have often caused great variation in the total amount of heat given to the earth by the sun (see Chapter VI).

The amount of dust in the air is readily measured by the Aitken dust-counter, which is a most ingenious instrument (Fig. 28). Here air can be sucked in at a tap A into the box X, by means of the piston P (tap B being open). This air can be rarefied greatly by shutting A and giving numerous strokes of the air-pump P.

In the box X is a lens above, a glass floor beneath, and damp filter paper at the sides. The air is thus saturated with water, and drops of water condense on each dust particle. They are thus made to fall on to the glass floor, and soon the air is freed from dust.

Now a small *known* quantity of dusty air is introduced into the dust-free air in the box. On withdrawing the piston P this air is rarefied, thereby cooled, and the dust falls on to the plate in the form of little silvery stars of moisture. These can readily be counted through the lens, and show the amount of dust in the small quantity of air tested.

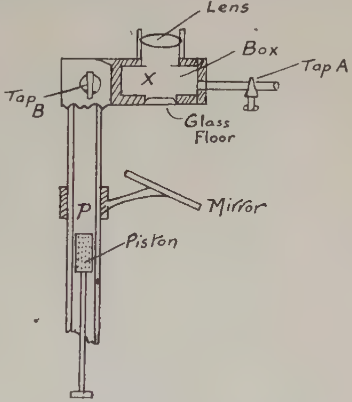


FIG. 28. Aitken Dust-counter. (Somewhat diagrammatic.)

Numerous observations were made in 1909 by Mr. E. T. Quayle in Victoria,[1] and are here summarized. They have an important bearing on the health of Melbourne.

He showed that in Melbourne any wind is better than none, for most dust particles occur in calm weather. The northerly winds (contrary to expectation) were the most free from the smaller dust particles.

RELATION OF DUST AND WINDS AT MELBOURNE

Wind Direction.	*Dust Particles per cubic inch.*	*Observations.*
North	509,000	39
North-west	672,000	9
West	733,000	26
South-west	650,000	13
South	663,000	15
South-east	617,000	4
East	695,000	6
North-east	817,000	16
Calm	918,000	17

[1] *Australian Monthly Weather Report*, Melbourne, July 1910.

A dense fog on June 29, 1909, gave 1,902,000 particles: while the lowest (128,000) was on a wet day with north winds.

Mr. Quayle also tried the counter on Mount Buffalo (120 miles NE. of Melbourne) at a height of 4,500 feet. Here the number was only 4,900 after a night of heavy rain.

Milham gives 1,640,000 particles as by no means a large number for a dusty city, so that Melbourne is not a particularly dusty locality.

Dust and the Colour of the Sky

The sun gives off light-rays of many wave-lengths. The shorter, quicker waves give rise to blue light; the longer, slower waves to red light. Yellow and green lie between these, and the total effect is that the light appears white.

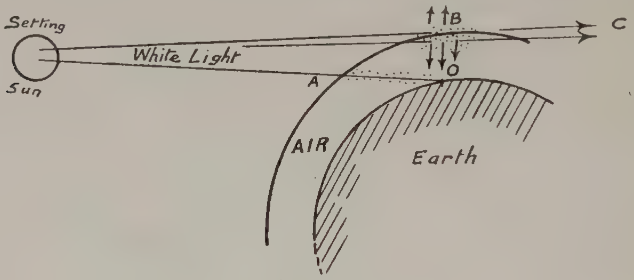


Fig. 29. Blue light of the sky.

The colours of the sky are chiefly due to the fine particles of dust which are present throughout the atmosphere. These particles act like a sieve and allow the longer red waves to pass them but block the shorter blue waves, which are reflected away from them in all directions.

Thus an observer at o (Fig. 29), when the sun is setting, receives direct light from the sun along the line A O. This has passed through many miles of turbid air, and only the colours due to the longer waves can get through. Hence the light is largely red and yellow, and this colours the clouds around the setting sun.

If we look overhead at this time we often see that the sky is a deep blue. This is because the light from that quarter is chiefly blue light reflected down from the particles of dust at B. The red portion of the white light reaching the atmosphere at B has largely passed on toward C.

The Molecular Structure of the Atmosphere

We are to picture the atmosphere as an intimate mixture of myriads of molecules of the various gases mentioned previously. These are all in motion revolving about each other in complicated but very minute orbits. They are suffering collisions, deviations, and accelerations, but are controlled by definite physical laws.

They are held *to* the earth by the pull of gravity, and they tend to move away *from* the earth owing to various causes.[1] Possibly on the extreme outer margin of the atmosphere the repulsion is greater than the attraction, and so the earth is losing some of its lightest gases.

In the inner layers of the atmosphere—which are all that concern us—the changes in temperature are the chief factors which affect the molecules. When the temperature increases, the molecules vibrate more rapidly. They therefore exert more force on any substance by which they may be confined ; in effect the gaseous *pressure* is increased.

As we shall see later, the molecules in water are also vibrating, but not sufficiently to overcome their affinity for similar molecules. Hence they remain together, forming a liquid. But if the temperature is increased they vibrate more freely, and ultimately the inter-molecular attractions of some molecules are overcome, and they fly off into free orbits.

This is approximately what occurs during evaporation (see Chapter XII), and when the operation is prolonged sufficiently, all the molecules may disappear from sight as vapour.

Height and Variation of the Atmosphere

Although our atmospheric envelope merges imperceptibly into the ether of space, yet there are many observations which show us that for all practical purposes there is a definite upper limit. This is found to lie farther away from the earth, according to the delicacy of the experiment which we carry out.

We have seen from our experiments with the barometer that if the atmosphere were so held to the earth that it was of uniform density throughout, then the layer of air would be about five miles thick. But we know that as we ascend above sea level the air becomes less dense. There are fewer molecules per cubic centimetre—or in other words the atmospheric *pressure* is less.

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[1] Pressure due to light and molecular velocities over seven miles per second have been suggested. (Vide *Atmosphere*. A. J. Berry, 1913).

As we climb a high mountain—over 10,000 feet—many of us would begin to experience ‘mountain sickness’, which is due to the effect of this unusual ‘thin air’ on our lungs. At much higher altitudes only specially seasoned climbers can withstand the weakening effect of the change environment. Yet a height of some 22,000 feet has been reached in the Himalayas by the party led by Bullock Workman (Fig. 30).

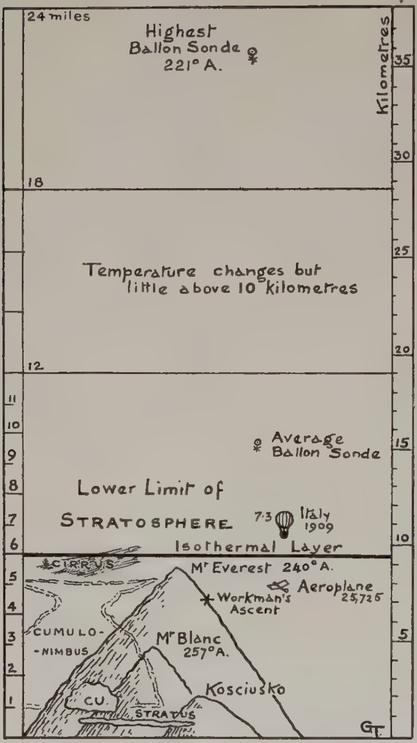

FIG. 30. ‘Man's Conquest of the Air.’ The troposphere lies below the heavy horizontal line at six miles elevation. The huge extent of the thunder-cloud (cu. nimbus) is indicated by the double outline. (Based on Napier Shaw.)

Although the number of molecules per unit capacity is here reduced to less than half the normal amount, yet the proportions of oxygen, nitrogen, and argon are found to be practically the same as at ordinary levels.

Another method of reaching the higher levels of the air is by means of aeroplanes. These have ascended to 27,000 feet.[1] But balloons can rise far beyond this level. In 1901 Berson ascended above Berlin for some 30,000 feet, and this record was beaten in 1909 by the Italians, who reached 38,700 feet. In both these cases they were provided with cylinders of oxygen to enable their lungs to carry on their function.

As regards the change in the proportions of the gases of the upper air atmosphere, this was summarized in 1909 by Humphreys. He states :

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[1] In January 1919, an Australian aviator (Lang) reached 30,500 feet over England.

1. That water vapour is present to the extent of 1.2 per cent. of the total gases at the surface of the earth, and that it decreases rapidly with increase of elevation. There is only an imperceptible amount present at 10 kilometres.

2. That beyond 11 kilometres above sea level (in temperate latitudes) the temperature remains almost constant at about −55° C.

3. That above this level the several gases distribute themselves according to their respective molecular weights.

Thus at 50 kilometres the proportions have altered greatly, and at 100 kilometres they bear no resemblance to those at the surface.

	Percentage by Volume.			
Height.	*Nitrogen.*	*Oxygen.*	*Hydrogen.*	*Helium.*
100 kilometres . .	1·6	0·07	97·84	0·46
50 kilometres . .	86·16	10·01	3·72	0·03
Surface . .	77·1	20·75	·01	—

The most fruitful source of our knowledge as to the conditions of the upper air is the ballon-sonde. This is a small rubber balloon about one metre in diameter, which is filled with hydrogen. It carries up a set of light instruments called a meteorograph. In a later chapter we shall read of the results obtained by this upper air research. Here it is sufficient to note that these small balloons have risen considerably over 20 miles (Fig. 30).

Faint luminous clouds—mere wisps of delicate greys and greens—are observed in midsummer above polar regions. They are found to be about 80 kilometres high, and are supposed to be due to ice crystals. If this be so, there must be an appreciable atmosphere—but it may be remarked that all other ice-clouds are even lower in polar regions than elsewhere.

Indirect experiment is necessary to ascertain the character of the atmosphere above this height. Thus the light from shooting stars can be examined in a spectroscope. Various lines are here visible which prove that the heated body is moving through an atmosphere, which largely consists of hydrogen. This is what we should expect, as this is the lightest gas. It is emitted from many active volcanoes, and rises rapidly through the denser gases (oxygen and nitrogen) until it reaches the outer layers of the atmosphere.

CHAPTER V

INSOLATION AND ITS VARIATION

If we consider how isolated the earth is in its swing through space, how removed from controls which can affect it by the surrounding sea of imponderable ether, it should be a matter of surprise that the atmosphere is not as stable and regular in its movements as the hydrosphere. And yet we know that nothing is so variable as the weather. What, then, is the prime cause which produces these varied currents in the air—these alternations of heavy cloud and clear blue sky—these sheets of driving rain, and all the manifestations which culminate in the fury of the hurricane?

The only important agent of which we have knowledge is the sun's heat, and to this great source of energy as it acts on the varying constituents of the atmosphere are due almost all the varied phenomena which make up the science of meteorology. We may, therefore, fittingly commence our study of temperature by considering how the sun heats the earth.

INSOLATION. The sun, like all other hot bodies, sends out waves of heat in all directions. Only a very small portion of those waves strikes the earth, for the sun could warm two billion earths like ours to the same extent. This energy from the sun has been given the special name of *insolation* (from the Latin *sol*, the sun).

Meteorology is concerned almost wholly with the *heating* effect of insolation, and this supply of heat is a form of energy, and does work, just as does coal when it is burnt to drive a locomotive.

Milham states that enough heat is received from the sun every year to melt a layer of ice 241 feet thick over the whole earth. Since, as every one knows, there is an enormous ice-cap on Antarctica (which is estimated to be 2,000 feet thick, and which remains almost constant in amount), it is obvious that the distribution of insolation over the earth's surface must vary very greatly in different regions. This is of course true, though it is a paradox that the South Pole receives more heat in twenty-four hours at midsummer than does the equator in a similar period!

Several factors determine how much heat shall be received from the sun at any spot, some of which are shown diagrammatically in Fig. 31.

Distance from the Sun. On 1 January the earth is 3,000,000 miles nearer the sun (Perihelion, 91,341,200 miles) than on 1 July. (The fact that this happens at the beginning of our year is a pure coincidence.) At this date the sun is directly overhead about latitude 23½° S. (i. e. over northern Australia), and Antarctica is receiving continual sunlight throughout the twenty-four hours. The earth moves in its elliptical orbit (whose axes are 94,000,000 and 91,000,000 miles) toward the other end of its orbit.

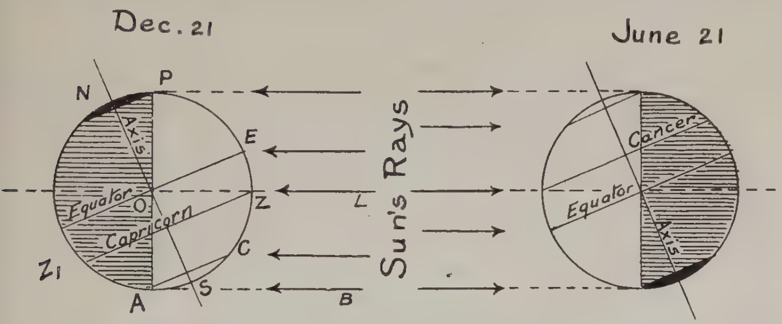


Fig. 31. The meaning of the tropics and polar circles. The sun is so far distant that the rays are practically parallel. The ray directed to the centre of the earth always shows the *overhead* sun. The black regions have no daylight in the 24 hours.

On 1 July the earth is at the farthest distance from the sun (Aphelion, 94,450,700 miles), and now no portion of Antarctica is receiving any insolation. But the North Pole—though also bathed in light for the whole twenty-four hours—receives less than did the South Pole, for it is so much farther away.

Inclination of Earth's Axis. The peculiar conditions occurring at the Poles are due to the earth's axis (NS) not being perpendicular to its orbit (OL) round the sun, but being inclined at 23½° to the perpendicular (PA) (see Fig. 31). The sun's rays come from an almost infinite distance, and so are parallel as shown. The angle NOP is the angle 23½° mentioned above. Draw a perpendicular OZ. Then NOP equals EOZ; and it is clear that Z is the point vertically beneath the sun. As the earth rotates about NS, all points on the latitude ZZ_1 come beneath the sun. This latitude (when the overhead sun is farthest from the equator, to the south) is called the tropic of Capricorn.

The sun's ray BA just grazes the earth at A, and so on the daily rotation of the earth about NS all the surface south of the latitude AC remains in the sun on 21 December. This latitude is called the Antarctic Circle.

A rough model of the earth should be made—say from a ping-pong ball—with the axis in the form of a long hat-pin. Mark the lines on the ball to represent the equator and other latitudes mentioned. Tilt the axis 23½° from the vertical, and draw an elliptic orbit on the table (whose axes are as 91 to 94). Place another hat-pin at the centre of the orbit, whose knob can represent the sun, and experiment with the earth at the two extreme and two middle positions of the orbit round the sun. It is vital to keep the axis aways parallel in all its positions.

At Aphelion the axis slopes so that the north pole is nearer the sun. The region within the arctic circle is bathed in light for practically twenty-four hours. At the equinoxes (the two mean positions half-way between the other two) the rim of the lighted face of the earth passes through the two poles, so that every place on the earth has equal day and night. (This should be tested with the model.)

It follows that only on two dates (the equinoxes, 21 March and 23 September) is the equator the nearest place to the sun.

The sun therefore (apparently) moves across the heavens from east to west in a spiral path. If we imagine a plumb-line hanging from the sun to the earth the plumb-line will mark out a spiral all round the region between the tropics. And we can easily estimate approximately how this spiral will lie (see Fig. 32).

On 24 September (from the *Nautical Almanac*) we find that the sun will be overhead about 19½ miles south of the equator. At noon on the 25th he will be overhead at 43 miles south of the equator. Thus he has moved south about 24 miles in 24 hours, or one mile per hour.

But in each hour he has moved to the west just 15°, or 900 miles per hour measured along the surface. We can therefore plot out the track our 'solar-plumb-bob' would mark on the earth (see Fig. 32).

As the sun approaches the tropics his apparent movement to the south becomes much slower, and it is only at the equator that this movement approaches one mile an hour. On 21 December he seems to *halt* on the Tropic, before returning. This date is therefore called the Solstice, which is the Latin for *Sun's Halt*.

THE INCIDENCE OF THE RAYS. The amount of insolation received from the sun depends also on the incidence of the sun's rays—that is on the slope the earth's surface presents to the sun. This is clearly shown in Fig. 33. If the sun is nearly *overhead*, as in the tropics at mid-day, a certain amount of insolation, which we can limit by passing it through a circular hole in a screen (at A, as in the stop of a camera), will be concentrated on the *same area* of the surface of the earth.

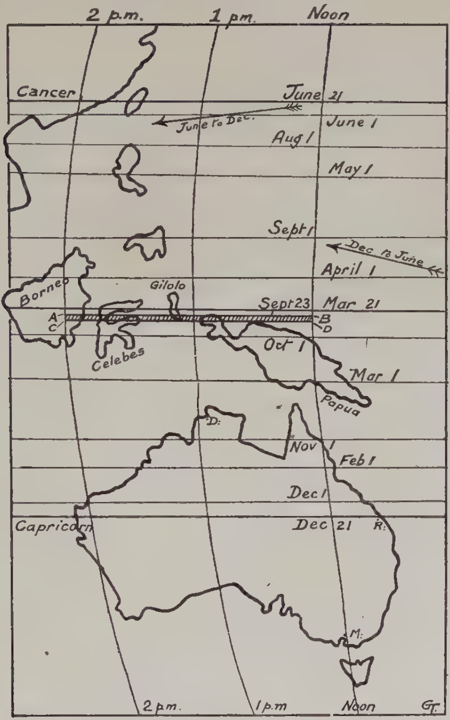


FIG. 32. Map showing the approximate overhead positions of the sun at various dates—referred to Melbourne local time. The arrows show the slight southing (June to December) and northing (December to June) much exaggerated. BA shows approximately the track of the overhead sun from noon on 24 September to 2 p.m., DC shows the track just 24 hours later. The sun has moved 1 mile south and 900 miles to the west in each hour.

But in the *polar* midsummer the sun is never overhead, and even in midsummer the sun's rays passing through the same aperture would be scattered over a large area of the earth's surface, for the latter is now very oblique to the direction of the rays. The insolation will therefore have very much less heating effect per square foot.

The Duration of the Rays. The amount of insolation is of course proportionate to the duration of time in which the sun is acting. For instance there is a very great difference in the heating experienced in Antarctica in mid-January and in mid-March.

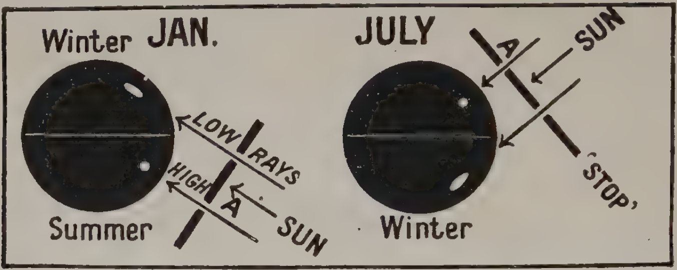


Fig. 33. The incidence of the rays. In winter the same insolation is spread over a larger area.

The sun in latitude 78° S. shines continuously in the former month, in the latter it has commenced to dip below the horizon for an hour or so each side of midnight. The tremendous Antarctic cold increases rapidly when once the sun has set, and is not fully dissipated with the sun's return next day.

This is perhaps the chief reason why Amundsen had a comparatively easy return journey from the Pole in January, while Scott's party was delayed and finally destroyed by the severity of the polar cold in March.

We now see that the amount of insolation received at any spot (which is the chief factor in determining the climate and weather there) varies according to three conditions. These are nearness to the sun, directness of the rays, and the duration. We have learnt that these depend on two factors—time and latitude.

We can show these variations graphically, as in Fig. 34, which is taken from Milham. Here the unit of insolation (1·0) is the amount of heat received at the equator on the hottest day (21 March). We see very clearly that there are *two* hottest periods at the equator.

Moreover, a day in mid-June receives more heat at the North Pole (1·2) than any at the equator. But there is darkness at the North Pole from 23 September until 21 March.

In these graphs there is no allowance made for the amount of solar heat absorbed by the blanket of air which surrounds the earth. This very greatly reduces the insolation, especially at the Poles, where the layer to be penetrated is very thick, as may be deduced from a glance at Fig. 35.

RADIATION

Since the earth keeps the same average temperature from year to year, it is evident that the heat from the sun is not accumulating, but is being lost to space at much the same rate as we receive it. This loss of heat is called radiation, and it is very noticeable at night. It gives rise to many important meteorological phenomena.

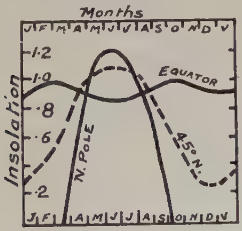


FIG. 34. The variation in insolation with latitude. (From Milham.)

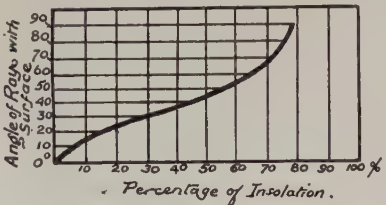


FIG. 35. Effect of atmosphere on insolation. The horizontal lines show the amount received at various angles of incidence. (Data from Hann.)

Maurer found at Zurich that during three cloudless nights in June a blackened copper plate radiated one-tenth as much heat per minute as was received from the sun at midday. Even at midday with a clear sky a loss of heat occurs through radiation, which is often as strong as on clear nights. During the day, even if the heavens are clouded, there is always a supply of heat passing from the sky to the earth, which is greatest in the forenoon and is sometimes greater than the radiation to a clear sky. In the night, radiation from the earth to the sky occurs whether the sky is cloudy or clear (though much more in the latter case). Even if a night, starting clear with low temperatures, becomes clouded later, yet the radiation continues right up to sunrise (vide Hann).

INSOLATION AND ATMOSPHERE

In the last chapter it has been shown that the insolation received on the earth's surface varies very greatly, according to the locality and the season of the year. We must now consider how the atmosphere affects it.

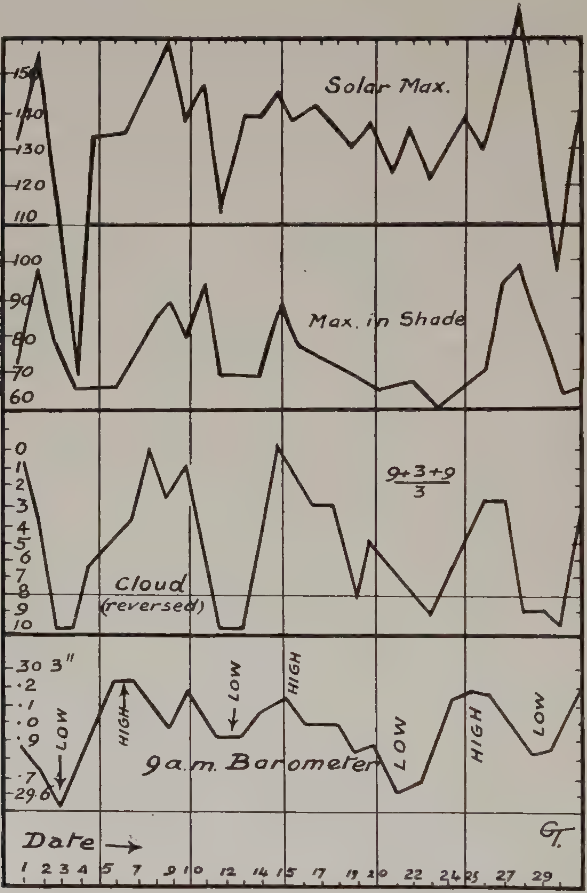


FIG. 36. Solar, maximum, cloud and barometer values at Melbourne for January 1909.

If the sunlight shines on a portion of the earth's surface at 90° to its path, about 22 per cent. is absorbed by the atmosphere. If the surface is parallel to the rays (0°), so that the latter *glance* along it, obviously none of the heat will be received by the surface (see Fig. 35).

The intermediate conditions are shown in the graph (Fig. 35). This shows how hot is the true *overhead* sun (i. e. in the Tropics) compared with his effect in the cooler regions where he is never overhead. It also emphasizes the feeble power of the sun in polar regions where he only rises 47° above the horizon at midsummer on the Antarctic circle, and 23° at the Pole. The amount of insolation received on the earth in these regions does not often exceed 25 per cent. of that which arrives at the outer limit of the atmosphere.

Interesting experiments by Crova in 1888, at the Observatory of Montpellier in Southern France, show that where the atmosphere is thinner by 2,000 metres (as on Mont Ventoux above the town), the insolation received during the sunny hours of the day increases by nearly 50 per cent. as compared with that recorded in the town itself.

THE TRANSFER OF HEAT. We must carefully distinguish between the insolation effect on a special instrument (e. g. a thermometer with a *black* bulb in the sun) and the normal temperature of the air, which is measured quite otherwise.

This is shown in Fig. 36, where data for January 1909 are plotted. On 27 January, 1909, the solar (black bulb) thermometer rose to nearly 170°. At the same time the shade temperature was only 100. The cloud distribution is shown (in a reversed graph) just below, and finally the 9 a.m. pressure variation. There were four well-marked Lows and three well-marked Highs which passed Melbourne in the month. The corrélations of pressure with cloud and solar heat can readily be recognized.

Suppose we place a thermometer 3 feet from a glowing fire. Its temperature rises enormously, although the *air* there may be 30° cooler. The air receives its heat from the warmed floors, walls, furniture, &c., and not so much from the heat rays passing through it. (If the thermometer be swung in this air and shielded from *direct* rays the mercury falls at once.)

In the Eiffel Tower, instruments at the base and at the top (1,000 feet higher) give very interesting records. They show that the maximum heat of the day occurs one hour later at the top than at the base. So also the minimum temperature occurs one hour later (see Fig. 37). It can be easily shown that this hour is occupied by the heat wave (or cold wave) in passing from the ground to the air 1,000 feet above. In other words the upper air receives its heat by conduction or convection *from the earth's surface.* We see a similar (but slower) case of heat transfer in

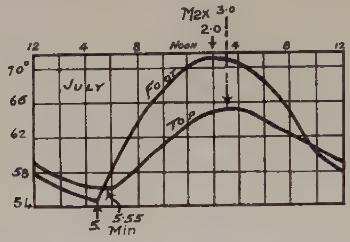


Fig. 37. Eiffel Tower Records proving that the air is warmed from below. Note the 'lag' is one hour in both maximum and minimum. (After Lake.)

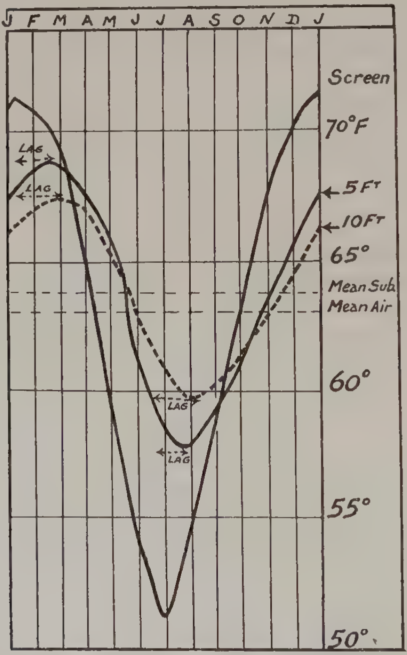


Fig. 38. Sydney underground temperatures, 5 and 10 feet deep, and screen (air) temperatures. Note the lag in the heat transfer. (Based on forty years record.)

the Sydney ground temperatures in Fig. 38. Here the heat maxima and heat minima take about one month to descend 5 feet, and about six weeks to reach 10 feet.

CHAPTER VI

TEMPERATURE VARIATION AND DISTRIBUTION

Daily Variation. In an earlier chapter we have seen how temperature is measured, and we have learnt that (unless otherwise stated) this temperature applies to the average free air conditions about 4 feet from the ground. The temperature of the ground, or that of a thermometer bulb freely exposed to the sun, is quite different.

At first glance one might expect that it would be coldest at midnight and warmest at midday. But it is found that there is a delay or ‘ lag ’ in the heating of the air, so that though the sun’s radiation is greatest at midday the air shows the highest temperature in Melbourne about 2 p.m. This is because the air is warmed from the ground, as has been explained previously.

If we examine an average temperature record—such as the first day on the thermograph shown in Fig. 39—we see that the temperature at Melbourne rises and falls about 18° F. each day. The average figures are given in the following table, which is based on sixty years record.

Temperatures at Melbourne

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Mean maximum .	78·2	77·9	74·5	68·4	61·4	56·8	55·5	58·8	62·5	67·0	71·5	75·3	67·3
Mean minimum .	56·7	56·9	54·7	50·7	46·7	44·0	41·6	43·4	45·5	48·1	51·1	54·0	49·4
Mean range . .	21·5	21·1	19·8	17·8	14·8	12·8	13·9	15·4	17·0	18·9	20·4	21·3	17·9
Extreme maximum .	111·2	109·5	105·5	94·0	83·7	72·2	68·4	77·0	82·3	98·4	105·7	110·7	—

On many days, of course, these *mean* monthly ranges are exceeded ; for instance on 31 December, 1862, when the range was 55·5 degrees ! In the example illustrated (for the week 19–25 October, 1914) the range is also very high, approaching 40 degrees (see Fig. 39).

If we look specially at the curve for 22 October (Fig. 39) we see the shape of a typical daily thermometer graph. The lowest temperature of the day was at 4 a.m. The air heated rapidly after sunrise to a maximum at 2 p.m. It then dropped in temperature as rapidly to 4 p.m., but thereafter cooled much more slowly, reaching a minimum at 4 a.m. on the 23rd. If the air had cooled as quickly as it warmed, the thermograph trace would have followed XY and given a minimum at 10 p.m. The slower cooling is largely due to the greater amount of moisture present in the air in the afternoon.

Variations of a similiar nature occur in other stations—though as we move into the tropics, the temperature range is of a different character. Thus at Darwin the figures (based on 33 years) are as follows :

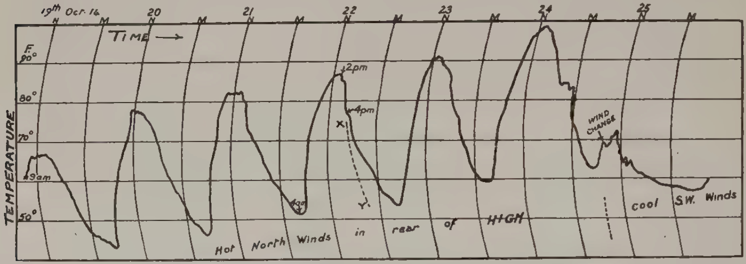


FIG. 39. Thermograph illustrating a heat wave at Melbourne due to an almost stationary High over the New South Wales coast. XY is the line of symmetrical cooling.

TEMPERATURE AT DARWIN

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*
Mean maximum .	90·6	90·1	91·4	92·6	90·8	88·3
Mean minimum .	77·3	77·9	76·9	75·9	72·6	69·1
Mean range .	13·3	12·2	14·5	16·7	18·2	19·2
Extreme maximum .	100·0	100·9	102·0	104·0	102·3	98·0
	July	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Mean maximum .	87·3	89·4	91·6	93·7	93·8	92·7
Mean minimum .	67·0	69·4	73·7	77·0	77·7	78·0
Mean range . .	20·3	20·0	17·9	16·7	16·1	14·7
Extreme maximum .	98·0	98·0	102·0	104·9	103·3	102·0

A comparison of these two tables show us that the daily range is greatest in summer in the south, while at Darwin (in the tropics) it is greatest in winter. This is chiefly due to the long succession of clear nights in the dry tropical winter. Radiation from the ground is then very pronounced, owing to the absence of the cloud blanket, and so the temperatures fall during the night nearly twice as far as they do in summer.

ANNUAL VARIATION

Australia is a large area of land, and includes not only temperate but tropical climates. The distinction is important, especially in regard to the phenomenon we are now considering.

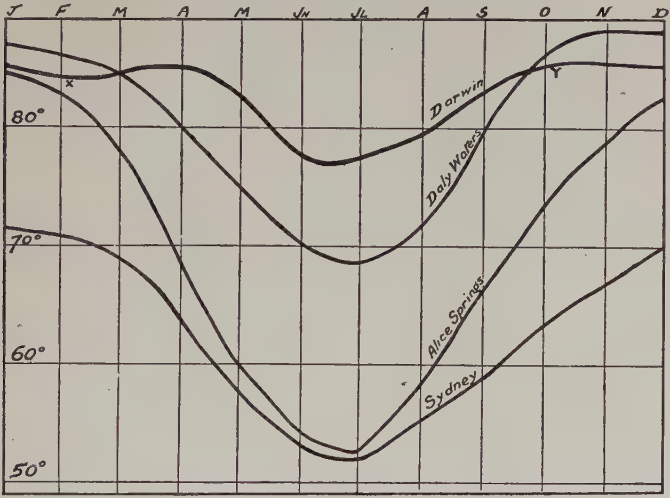


FIG. 40. Characteristic temperatures of two inland and two coastal localities. x shows the slightly cooler midsummer at Darwin.

The temperature of a place depends primarily on the position of the earth with regard to the sun. Just as the daily rotation of the earth on its axis gives rise to the daily variation we have just considered, so the (apparent) annual movement of the sun from the tropic of Cancer to the tropic of Capricorn is the chief factor in controlling the annual variation in temperature.

We have seen previously that during the summer the sun is overhead in Northern Australia. Towards the end of October he reaches our northern coast at Thursday Island and Darwin. At the end of November he is over Mackay, and at the end of December over Rockhampton, which lies at his turning point on the tropic of Capricorn (Greek *tropos*, a turning). He returns north at a similar rate and passes over Darwin again at the end of February (see Fig. 32).

Thus for temperate Australia the hottest period occurs after the southern solstice (the sun's turning point) on 22 December. But in tropical places such as Darwin there are two hottest periods (in November and March), while January and February—which are the hottest months in the south—are there slightly cooler (see Fig. 40).

In Fig. 41 is shown the temperature change throughout the year for Melbourne. It is based on a succession of five-day periods, and so it enables us to tell more accurately than in the usual monthly graph, when are the hottest and coldest periods in the year. Although the whole period from 1879 to 1898 is used for the averages, we see that the curve is by no means a simple one, but contains well-marked minor waves.

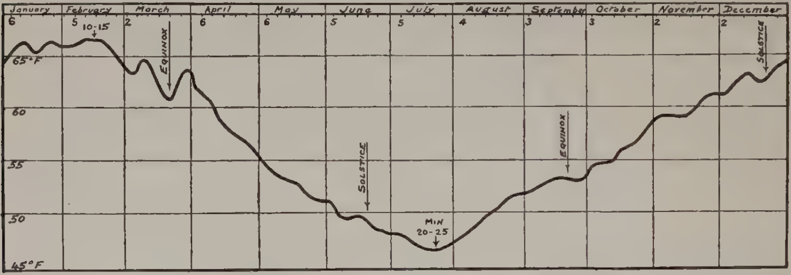


Fig. 41. The march of the temperature throughout the year at Melbourne. Based on five-day intervals during 1879–98. Note the marked fluctuations which occur in March. (Partly after Barnard.)

The hottest period in Melbourne is usually from the 10th to the 15th of February. There is thus a 'lag' of fifty days after the time when the sun is farthest south, before the air is warmed up to its full summer heat.

The coldest period is from the 20th to the 25th of July, which is a 'lag' of thirty days after the winter solstice.

The three summer months in temperate Australia are December, January, and February. As we can see, March in Melbourne is as warm as December, but it is considered to belong to Autumn with April and May. June, July, and August are the winter months, and are quite sharply defined, while September, October, and November are the spring months.

The irregularities noticed in the temperature graph for Melbourne are most characteristic near 20 March and amount to several degrees, while others occur in June, September, and December. Similar reversions from warm to cool weather and vice versa are also found in Adelaide at the special dates.

They are seen to agree approximately with the critical periods in the sun's path (i.e. the two solstices and two equinoxes), but this may be accidental.

In Europe a similar fluctuation is apparent in June (*vide* Hann). Here there is usually a *fall* of a degree centigrade in the average daily mean from 13 June to 20 June. The phenomenon has, however, never been fully explained.

If we choose four type stations such as those shown in Fig. 40, we see that not only is the temperature lower at Sydney than at Darwin, but the range of temperature is greater at the former place. An inland town like Alice Springs has, however, a much greater range again, and these features are typical of all continents. Firstly, coastal places have a smaller range than inland places. Secondly, tropical places have in general a smaller range than temperate places.

A chart showing the range of temperature is given in Fig. 42, where we see the lines of equal temperature range lie close together near the southern coasts, farther apart near the northern coasts, and farthest of all in the interior of the continent.

PLACES WITH LOW TEMPERATURE RANGE

Tropical.		*Temperate.*	
Thursday Island (Q.) .	5·5° F.	Breaksea Island (W.A.)	11·0° F.
Darwin (N.T.) . .	8·2° F.	Cape Sorell (Tas.) .	12·0° F.
Cooktown (Q.) . .	9·9° F.	Cape Otway (Vic.) .	12·3° F.
Cairns (Q.) . .	11·9° F.	Robe (S.A.) . .	13·9° F.

The reasons for this are easily understood. The sea acts as the great equalizer of temperature. It heats up very slowly in summer—it cools very slowly in winter. Near the equator the Atlantic Ocean only varies about 3° F. in the year, and in latitude 35° N. about 12° F.

The ports and promontories in the above table are bathed by the ocean, and their temperatures are almost controlled by it.

At Fort Denison (in Sydney harbour) the sea varies as follows :

AVERAGE TEMPERATURES OF HARBOUR AT SYDNEY

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Sea (48 years) .	71·6	72·0	71·1	68·4	64·2	60·2	57·4	57·9	60·4	63·5	67·1	69·7	65·3
Land (56 years) .	71·6	71·1	69·2	64·6	58·5	54·3	52·4	54·9	59·0	63·5	67·1	70·1	63·0

Although Sydney harbour is enclosed to a considerable extent, yet it probably represents the ocean temperatures fairly well. The water has a range of 14·6° F., while the Observatory near by has a range of 19·2. The temperatures are nearly the same for the hot months. A short distance inland (Fig. 42) the range soon increases greatly.

The greatest range is in the interior, where the influence of the ocean is least felt. Bourke in New South Wales has an average temperature of 51·8° F. in the coldest month (July) and of 85·2° F. in the hottest month (January), so that the range is 33·4° F. This is the largest so far as our records show, though it is probable that the uninhabited desert region to the north-west of Wiluna (W. A.) experiences a greater range.

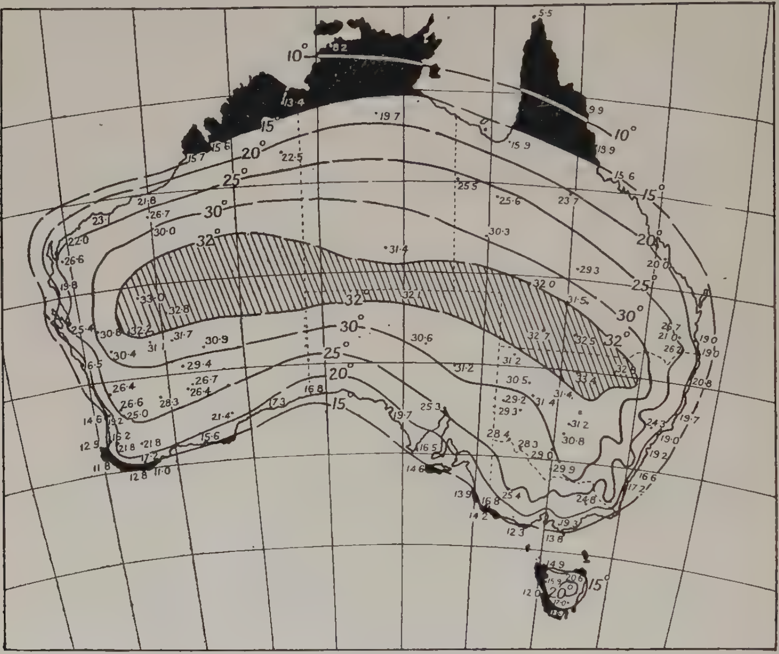


FIG. 42. Mean temperature range. Difference between mean temperature in hottest month and mean temperature in coldest month. Low range of temperature shown in black; high temperature range is ruled.

Owing to this difference in temperature range, localities may be usefully grouped into two classes.

Continental climates, remote from the coast and having great extremes of temperature.

Coastal climates, which are equable, milder, and vary much less, especially in the tropics.

These two classes are illustrated in Fig. 40. Darwin has a very slight range of temperature, for it is coastal and tropical. It shows the double maximum in summer. This is due to the sun being overhead twice (at X and Y), though the hottest months (November and March) occur a little later owing to the 'lag'.

As we move inland we see that the range increases, as shown at Daly Waters (Fig. 40). There is here practically no sign of a double maximum. In the centre of the continent is Alice Springs with a typical continental climate. Its summer is nearly as hot as Darwin, while its winter is almost the same as Sydney. Its range is therefore very great. Finally at Sydney we get a typical temperate-coast graph.

As we move nearer the Poles the range of temperature naturally becomes greater and greater—because at the Poles there is no heat supply for six months in the winter, and cooling by radiation has full sway. Hence the warming of our southern coastal regions by the ocean acts in opposition to this general increase in range (Fig. 42).

A study of the map shows that the chief oceanic effect reaches approximately 150 miles inland. Within this belt along our south coast the range increases by 6° F. per geographical degree as we move inland. At farther distances from the coast the gradient (or change per degree of 69 miles) falls to 1° F.

THE MONTHLY MARCH OF TEMPERATURE IN AUSTRALIA

The march of temperature (or movement of the isotherms) depends almost entirely on the sun's progress from tropic to tropic. Hence we might expect that the isotherms would run east and west; and advance and retreat with the sun, still keeping that direction.

But several factors modify the lie of the isotherms, so that they rarely run simply east and west. Of these the chief are:

(*a*) The group of highlands in the south-east, and

(*b*) The area of low pressure which forms in summer in the north-west of Australia.

There is also a marked tendency for the hinterland to be slightly warmer than either the coasts or the country considerably inland.

As a consequence the isotherms are somewhat complex curves, definite loops forming at each end of many of the isotherms.

These may be classified as Alpine cool loops and Hinterland hot loops.

In January (Fig. 43) the hottest region of Australia lies in West Australia, just behind Onslow and Cossack. Here the average temperature throughout the month is over 90° F. The same hot area persists through February and March (Fig. 44). There is a less marked tendency for a hot loop around Cloncurry, to the south of the Gulf of Carpentaria. (These form important centres of convection as described in a later chapter.) The eastern portion of the continent is no doubt benefited in summer by the south-east trade winds. In the south in these summer months the isotherms run more or less parallel to the south coast.

In April, when the sun is not far from the equator, the monthly chart is very nearly the same as that showing the average *annual* temperatures. The Wyndham and Darwin regions are over 85° F. There is a well-marked hot hinterland loop extending down the Queensland coast (e. g. 75° F.), and a cool Alpine loop (e. g. 60° F.) is creeping up toward Sydney from the south. In May (Fig. 45) and June the cool loop increases in extent.

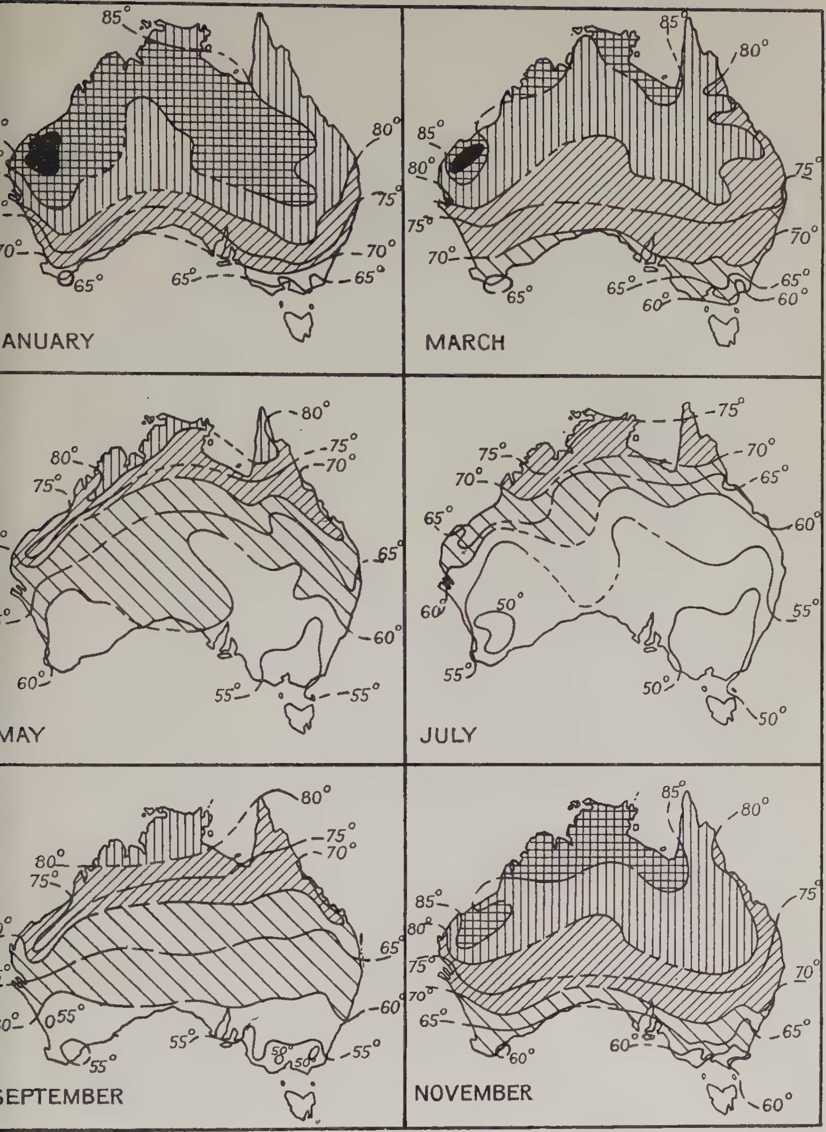
In July (Fig. 46), which is the coldest month, there are two regions below 50° F. The western includes Southern Cross and Katanning, but does not touch the coast; the eastern includes Tasmania, Victoria, and southern and central New South Wales. The New England Plateau accounts for the 50° loop extending so far north as latitude 30° S. (near Glen Innes). Around Omeo (Victoria) and Kiandra the average is below 40°.

In September (Fig. 47) the sun is approaching the equator from the north. The two hot hinterland loops have, however, already begun to form.

In November (Fig. 48) the sun has reached Darwin, and Northern Australia experiences temperatures over 85°. The hot loops so characteristic of the north-west and north-east have formed (see 85° F.), but elsewhere the isotherms are fairly regular.

ANNUAL ISOTHERMS

We can now consider the map showing the average annual temperature in Australia (Fig. 49). Several features which we have discussed in the monthly maps are so important that they have impressed themselves on the annual map.



ANUARY

MARCH

MAY

JULY

EPTEMBER

NOVEMBER

FIGS. 43–8. The march of the temperature in Australia (H. A. Hunt).

Thus while the Wyndham region on the whole is the hottest, the Pilbarra summer heat is shown by the hot loop along the Western Australia hinterland. In west Queensland the isotherms also show a relatively hot area south of the Gulf.

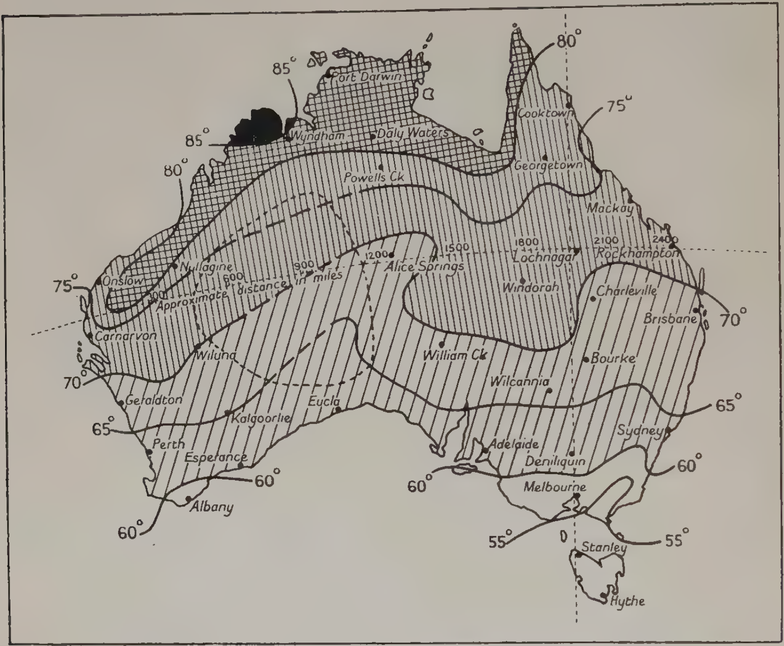


FIG. 49. Average annual temperature (after H. A. Hunt). The broken line in Western Australia includes the area without stations.

Alice Springs is somewhat of a cool 'island', owing to its elevation among the Macdonnell Ranges. The coolest region is of course Tasmania.

The chief ocean currents appear to exercise but little effect on the adjoining coasts. The warm current down the Queensland coast and the cold current flowing up the Perth coast may, however, give rise to some convection effects, as I suggest in a later chapter.

THE DISTRIBUTION OF TEMPERATURE OVER THE EARTH

The obvious way to plot temperatures would seem to be to draw the isotherms through all points having the same temperature for the period under discussion. But this is not always possible or advisable, especially in regard to world maps. In the first place there are only very few stations in many uncivilized or desert lands, and the elevation of the country often varies greatly within narrow limits. Secondly, for many meteorological purposes—such as in forecasting—it is better to view the temperature map without the complications due to a diverse topography.

Hence has arisen the convention in most countries (but not in Australia) of reducing the temperature to sea level. Thus if a station is 3,000 feet above sea level, and its average temperature is actually 63° F., a reduction factor of 1° F. for each 300 feet of ascent is employed, and the sea level temperature of the place is charted as 73° F.

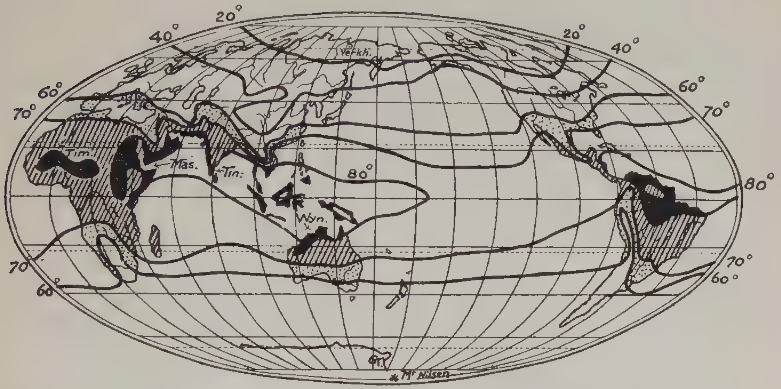


FIG. 50. Actual average annual isotherms—not reduced to sea level. The four hottest places, Timbuktu, Massowah, Tinnevelli, and Wyndham, are indicated. Note the 'cold loops' of Thibet, Mexico, Abyssinia, Rhodesia, and Peru. Mt. Nilsen is probably the coldest land surface on the globe.

As a result of this the isotherms run much more regularly east and west than they would otherwise do, and though we gain in simplicity, there is no doubt that we lose a great deal of the climatological value of the temperature maps.

In recent years our knowledge of the contours of the whole world has grown so greatly that it is now possible to get an approximate picture of the *actual* surface temperatures of the world. These are shown in Fig. 50.

It is to be noted that world maps have rarely been used for forecasting, while they are all important in problems of comparative climatology.

We shall find that many principles are illustrated in the map, which are obscured by the 'smoothing' of the isotherms in other world temperature maps.

The following broad features will be distinguished at once:

(*a*) The uniformity of the isotherms over the ocean as compared with their irregularity over the land.

(*b*) The equator is on the whole the warmest region, and the Polar regions the coldest; but both these statements need some modification.

(*c*) The western tropical coasts are usually colder than the eastern tropical coasts, while in the northern temperate regions the contrary is the case.

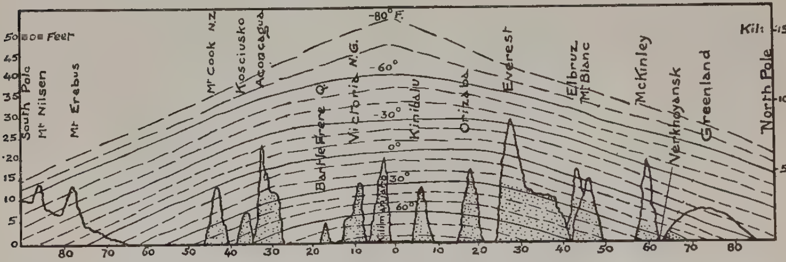


FIG. 51. Generalized diagram showing the relation of temperature to elevation and latitude. The coldest locality on earth is probably the summit of Mount Nilsen in Antarctica. (Below the snow line is dotted.)

Temperatures of free air are based on a few balloon results. Snow line is only approximate. Partly from Bartholomew's *Physical Atlas*, vol. iii.

(*d*) The heat equator is confined to the northern hemisphere, except in the Australian region (and perhaps in Brazil).

In the cooler regions we see the effect of elevation in the shape of Alpine loops. The two most noticeable are due to the plateau of eastern Thibet and to the Andes. But every highland has complicated the isotherms and radically altered the climate of such countries as Papua, Rhodesia, Abyssinia, Peru, Ecuador, Mexico, &c.

Owing to the North Pole being at the centre of the Arctic Ocean its temperature is relatively high. It is in Northern Siberia (at Verkhoyansk on the River Yana) that the coldest record (about —70° C.) has been obtained (Fig. 46). It is to be noted, however, that near the South Pole (where the whole plateau has an elevation of 11,000 feet) the temperatures will be much colder.

Thus the summit of Mount Nilsen (15,000 feet) is probably the coldest piece of land on earth, for at sea level Doctor Wilson recorded —61° C. when sledging *800 miles* north of the Pole, in midwinter 1911.

In Fig. 51 I have plotted many of the chief mountains in their appropriate latitudes, and added the approximate isotherms. The upper air data is only tentative, and is based on a few *ballon sonde* records. However, it serves to show that Antarctica is probably colder than the top of Everest. We also note that the limit of the troposphere, which is approximately separated from the stratosphere by the —80° F. isotherm, is higher at the equator than elsewhere Kosciusko does not quite reach to the snow line, but in New Zealand the Alps show much more snow than in Switzerland, because the country is somewhat cooler.

CHAPTER VII

ATMOSPHERIC PRESSURE AND ITS VARIATION

In earlier sections, concerning the weather map and the more ordinary instruments, the main principles underlying the measurement and plotting of atmospheric pressure have been described.

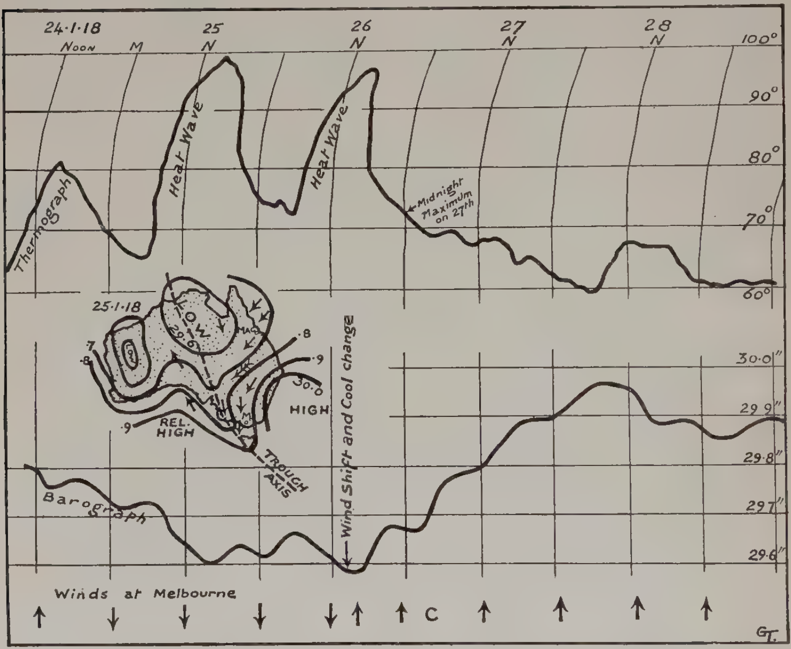


FIG. 52. Pressure, temperature, and wind changes due to the passing of a tropical trough over Melbourne, from 24 to 28 January, 1910. The weather map for 9 a.m. on the 25th is inset.

Its variation in time and space, however, is very important, especially if we wish to understand the general distribution of winds over the surface of the earth.

If we observe the graph drawn by the self-acting barometer (or barograph) we shall see that the curve has several marked characteristics. The period from crest to crest (the wave-length) is usually about a week. Thus in Fig. 52 a trough occurs at noon on the 26th, and the following crest at noon on the 28th. This is half a wave-length, and is shorter than usual, i.e. the full period is here four days.

The crests of the barograph correspond to the Highs and the troughs to the Lows, with which the reader is already more or less familiar.

Another feature is the presence of smaller waves superimposed on the main waves. These smaller waves are almost always present and are known as the diurnal variation. Each day, at most stations, shows a slight minimum at 4 a.m., followed by a maximum at 10 a.m. Then there is another trough at 4 p.m. and a slight crest at 10 p.m.

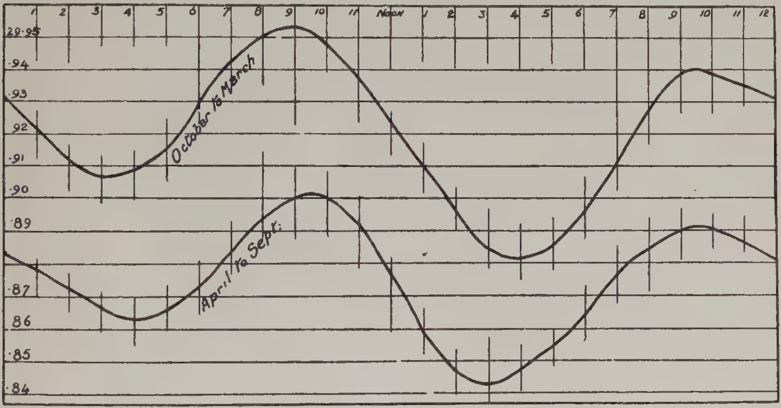


FIG. 53. The diurnal variation of the barometer at Melbourne, based on readings for the period October 1914 to September 1915. The top curve is for the hot months and the lower curve for the cool months. The maxima occur near 10 a.m. and 10 p.m., and the minima near 4 a.m. and 4 p.m.

Near the Equator this variation amounts to one-tenth of an inch—but in temperate regions the difference between the 10 a.m. maximum and the 4 p.m. minimum is usually 0.05 inch or less.

At Melbourne, as is shown in Fig. 53, the variation is 0.07 inches between the 10 a.m. reading and the 4 p.m. reading. The other two characteristic points at 10 p.m. and 4 a.m. are less noteworthy.

It is quite easy to pick out these small diurnal vibrations superimposed on the barograph curve given for the 25 and 26 January in Fig. 52.

THE DIURNAL VARIATION. The reason for these two daily swings of the barometer (see Fig. 53) is not well understood, but the following principles are involved.

In the afternoon the air as a whole is heated, and rises in consequence, flowing away east or west from the regions which are being heated by the sun. Thus pressure at the surface is diminished and we get the 4 p.m. minimum.

At stations above 3,000 feet a contrary effect is often noted, for the denser air is now temporarily rising to this level, and so a maximum is experienced about 4 p.m. in these layers.

Conversely in the night about 4 a.m. the air is chilled and settles down to the ground. This would lead to an increase of pressure, which however is not apparent. The chief control is probably dynamic, and is described below.

Convection currents (vertical currents of air due largely to differential heating of the surface) operate during the day and are absent at night. According to Humphreys (whom I quote freely) their greatest effect in mixing the stagnant lower air with the upper layer (which is usually drifting to the east) occurs about 10 a.m. Hence the damming-up of the atmosphere, and the resultant increase of barometric pressure (at any meridian) must increase most rapidly during the (local) forenoon.[1] This helps to explain the 10 a.m. maximum.

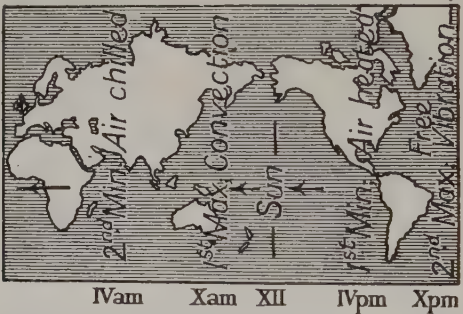


Fig. 54. The diurnal barometric 'tide' which moves westward around the globe with the sun. (Partly after Humphreys.)

To understand the 10 p.m. maximum we must refer to the theory of forced and free vibrations. A metal rod fixed at one end has a natural mode of vibration. If plucked about one-third of the way down it may vibrate *freely* in a series of vibrating loops separated by fixed 'nodes'. But by plucking it near by, it may be *forced* to produce vibrations of a slightly different length.

In the same way the whole atmosphere is a 'system' in which definite 'surges' or vibrations take place. It is probable that the belt of air over any meridian is set in forced oscillation by the sun so as to give a pressure crest at 10 a.m. and a trough at 4 p.m. This oscillation-period of 6 hours is very near its free period, so that *free* surges 'fit in' at six-hour intervals, giving rise to a maximum at 10 p.m. and a minimum at 4 a.m.

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[1] Humphreys. Bulletin on Diurnal Variation; Weather Bureau; Washington, 1912.

Thus at any instant when the sun is over the Pacific there is a 10 a.m. belt of maximum pressure over Australia and East Asia. The 4 p.m. belt is over America, the 4 a.m. minimum is affecting Europe and Africa, and the 10 p.m. maximum is over the Atlantic. Thus the four surges completely encircle the globe and move around it with the sun.

Altitude and Pressures. Since the density of the air decreases as we ascend, a convenient method of measuring elevation is given by the barometer. In general an ascent of 900 feet causes the barometer column to drop one inch. This means that we have climbed through a column of air which will balance one inch of mercury in the barometer. But this factor (one inch of mercury = 900 feet) is not constant, especially at high altitudes. It also varies slightly with the temperature.

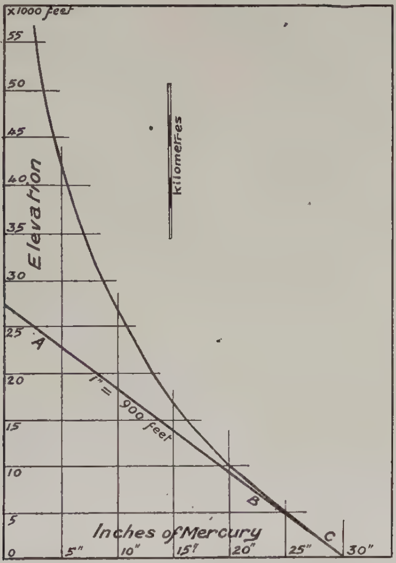


Fig. 55. The measurement of elevation by the barometer. Average figures up to ten miles are given by the curved line. The line A B C shows the effect of assuming a *constant* factor of 900 feet per inch of mercury.

In the graph (Fig. 55) the barometer readings for heights up to 10 miles (16 kilometres) are given fairly closely. If we assume that one inch of mercury *always* corresponds to 900 feet of ascent, then obviously at a height of about 27,000 feet there should be none of the 30 inches of mercury left in the barometer column.

This condition of *constant* decrease is indicated by the straight line ABC (Fig. 55). Since this line lies close to the accurate *curve* for the lower 10,000 feet we shall not be greatly in error if we assume one inch of mercury equivalent to 900 feet *within these limits*. But at a height of six miles one inch of mercury corresponds to about 3,000 feet, as we can see by measuring on the graph.

MONTHLY VARIATION IN PRESSURE

If the average monthly pressures be plotted for any Australian locality—such as Melbourne in Fig. 56—it will be found that the average pressure gradually increases from January to May, remains high during the cold weather, and falls rather rapidly to a minimum at midsummer.

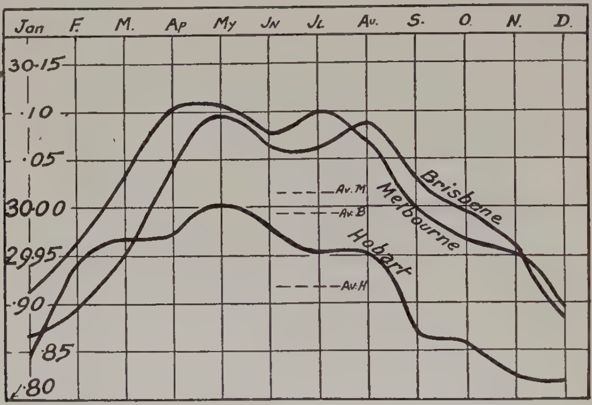


FIG. 56. Variation of barometric pressure throughout the year at Brisbane, Melbourne, and Hobart. (Averages are indicated in the centre of the graph.)

As we shall see later, a high average pressure usually means that the locality is under the influence of numerous anticyclones or Highs, while conversely the months having low pressure averages are those when anticyclones are less abundant. Further it is apparent that Melbourne has a higher average pressure than Brisbane (Fig. 56), while at Hobart the pressure is much lower than at either of these places.

The reasons for these variations will become apparent when the relations of the pressure belts to the march of the sun is considered.

The close relation between temperature and pressure is obvious if the various monthly pressure maps are compared with the similar series for temperature (Fig. 43).

Thus in January (see Fig. 57) there is a low pressure area (29·70 inches) in the north-west of the continent—which is correlated with the hottest region in Australia (see Fig. 43).

In March (Fig. 58) the isobars have moved north with the sun, and only a small coastal area near Darwin has pressures lower than 29·75 inches. The high pressures are also advancing from the south, and are beginning to occupy the belt from Melbourne to Newcastle. This march of pressure continues for the next few months, so that in May (Fig. 59) a belt of high pressure (over 30·0 inches) covers all south of the tropics, and the 30·15 isobar includes all central New South Wales.

In July (Fig. 60) the high pressure has intensified, so that all south of the tropics is now 30·10 (except a mere fringe in the extreme south). Hence the high pressure belt now lies wholly in Australia, with the maximum at Bourke (N.S.W.). Near this town is the highest annual (sea level) pressure recorded.

During the spring the isobars retreat southward with the sun. The march of the line of maximum pressure is shown approximately in Fig. 64. Thus the axis of pressure in September (Fig. 61) is much the same as in May—though the pressure as a whole is much less intense.

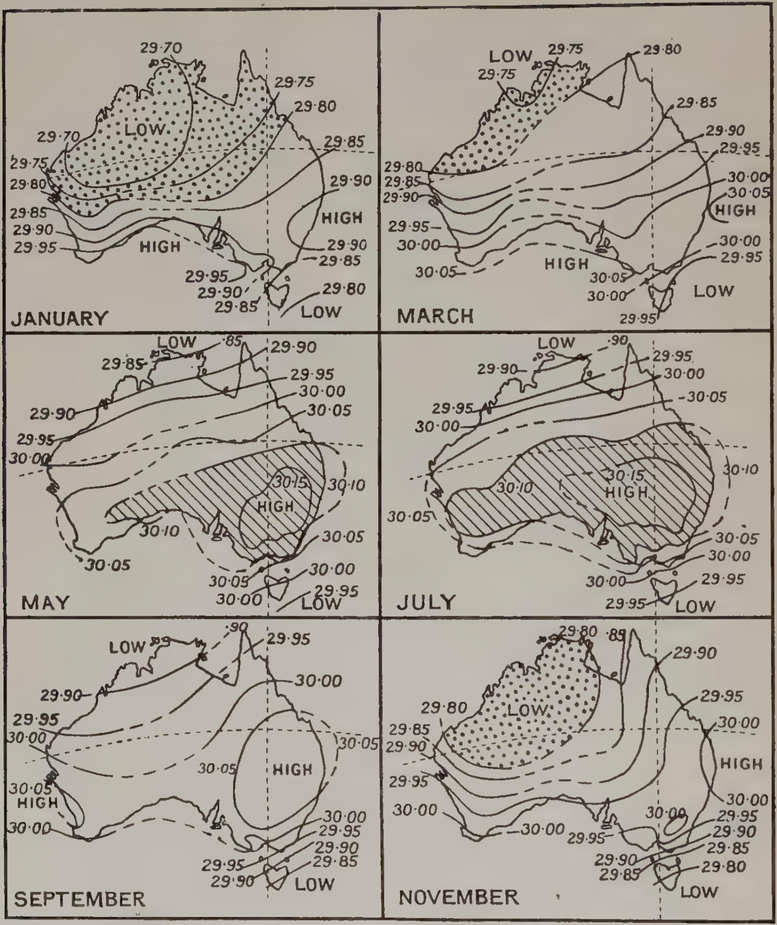
The high pressure is confined to the highlands to a greater degree in the spring than in the autumn, as is seen by comparing November (Fig. 62) with March (Fig. 58).

In December a centre of low pressure (29·70) has formed over Pilbarra (W.A.), precisely in the hottest portion of the continent, and this expands to cover the larger area shown in Fig. 57.

These figures (57–62), while representing average conditions, are rarely actually realized on any daily chart. They illustrate, however, two very important points in the daily charts. In midsummer it is obvious that the tropical cyclones (or Lows) have a tendency to hang about in the north-west over the heated land surface; while the anticyclones (or Highs) conversely favour the cooler water areas—the Bight and Tasman Sea—in that season.

Again in winter the Highs tend to occupy the cool south-east portion of the land surface, while very few long-lived Lows can affect the land at all, or their combined effect would appear in the *average* isobars for July.

The map for the average annual isobars shows of course the same main features (see Fig. 63). The high pressure belt of the southern hemisphere obviously passes through southern Australia from Cape Leeuwin through Adelaide to Clarence River (south of Brisbane).


JANUARY

MARCH

MAY

JULY

SEPTEMBER

NOVEMBER

Figs. 57–62. Mean monthly isobars. The low pressures are dotted, the high pressures are ruled.

The question of the dominant winds in any region is largely controlled by the average distribution of pressure. This topic will be discussed at length later, but the explanations of the drying easterly winds of Central Australia, the wet westerlies of Tasmania, and the striking monsoon changes in the north-west, are hinted at in these figures, especially in Fig. 63. The *dominant* winds must agree with the *average* annual pressure.

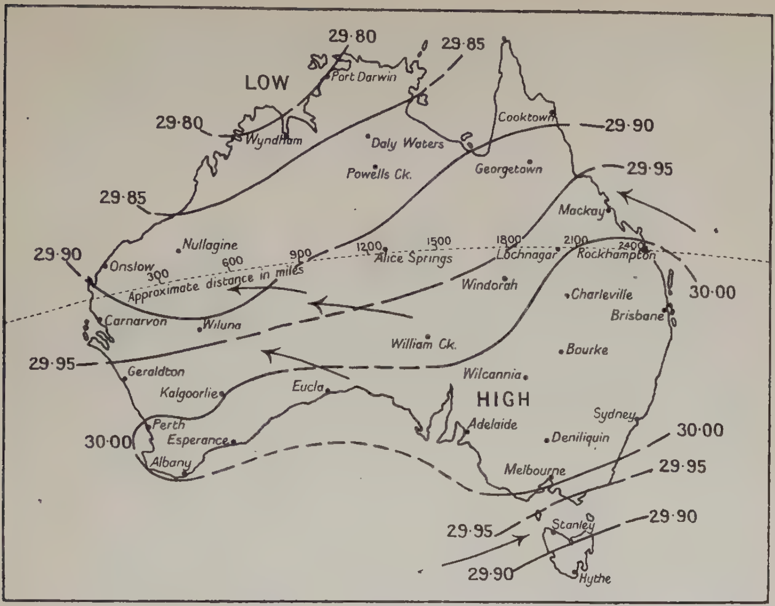


FIG. 63. Mean annual isobars. Some of the permanent winds are added.

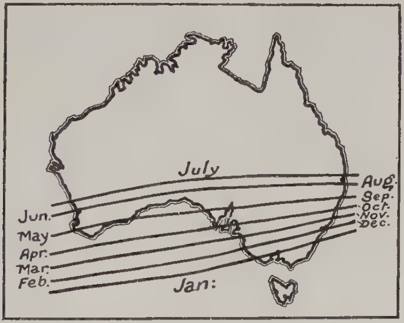


FIG. 64. Approximate positions of the average tracks of the Highs in the twelve months.

THE PRESSURE BELTS OF THE WORLD

The barometric pressure is lower in northern Australia than in southern Australia, and if an isobaric map of the world be consulted (see Fig. 66) it will be found that the pressure falls off both to the north and south of Australian latitudes. In Fig. 65 the average pressures are plotted in the graph to the right. Along latitude 35° S. is the belt of greatest world pressure, reaching 763·5 mm. (or 30·05 inches). This crosses southern Australia. To the north the pressure falls to 757·9 mm. at 10° N. latitude. Hence the equator is not in the centre of the equatorial low pressure belt, most of which lies to the north of it. Proceeding north again, another high pressure belt (762 mm.) is met with about latitude 40° N. (see Fig. 63); and a belt of low pressure, with an average of 758·7, lies near the Arctic Circle about 70° N.

Corresponding to this Arctic belt of low pressure there is an Antarctic belt of low pressure—where the average pressure is lowest on earth, being 739·7 mm. (or 29·11 inches). Thus the belt of highest pressure and belt of lowest pressure are adjacent—and this fact no doubt determines very largely the strength of the 'Brave West Winds' which blow in the 'roaring forties' between them.

At the Poles records are wanting, but it is certain that an area of high pressure (the South Polar Anticyclone) surrounds the South Pole. The latter is situated at a height of 10,000 feet, and probably has an average temperature of about −60° F. (see Fig. 51).

All round the Antarctic continent the dominant winds blow fiercely from the south-east. (These blizzards build up what Hobbs calls the Antarctic 'Broom' which sweeps the snow from the Pole to the periphery of the continent.) This counterclockwise circulation proves conclusively that there is a very strong and permanent High covering most of the continent. (See also the maps of the monsoon changes.)

In the Arctic regions is a very large area of water forming the Arctic Ocean. This is to some extent open water (at +28° F.) during the warmest months, which means that the temperature is much moderated.

More important barometric centres in the Arctic are found over the warmer waters of Iceland and over the chilled lands of northern Siberia; but the North Pole seems to reach a maximum of 30·1 inches in May and a minimum of 29·93 in September, with an annual average about 30·0 (*vide* Bartholomew). Dynamic theory suggests that possibly at moderate elevations (say 2 kilometres) the barometer is lower at the North Pole than at any similar level in the northern hemisphere.

Thus the atmosphere over the earth is arranged in a series of seven alternating regions or belts. The North Polar High (which is a shallow, feeble, fluctuating phenomenon), the Arctic low pressure belt, the northern high pressure belt, the broad Equatorial low pressure belt are in the northern hemisphere. The broad southern high pressure belt, the broad Antarctic low pressure belt, and the strong high pressure centre at the South Pole are in the southern hemisphere (see Fig. 65).

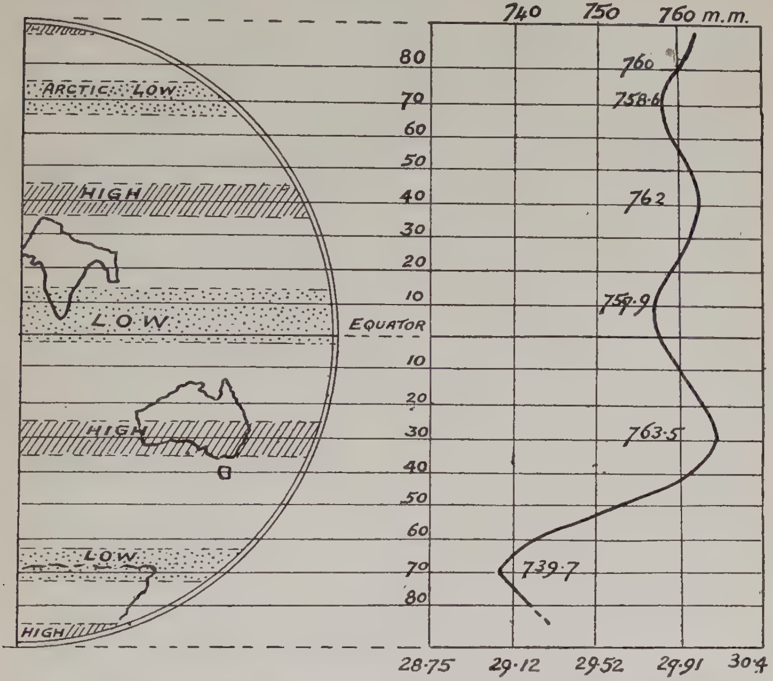


Fig. 65. The seven pressure belts of the world. Average pressures at sea level in various latitudes are plotted on the right. (From Hann.)

Pressure diminishes with distance above the surface, hence some little distance above the Australian high pressure belt pressures are reached equal to the various low pressure belts.

Thus about 800 feet above Australia we reach a zone with 29·0 inches of pressure—which is the surface pressure at 70° S. latitude. The isobaric surface for 29·0 inches is therefore warped down to sea level near Antarctica; but this average is only met with in the uplands of Australia, which reach up into this layer.

The isobars of the maps are therefore the intersections of these warped isobaric planes with a horizontal plane, i.e. the earth's surface at sea level.

ACTUAL DISTRIBUTION OF PRESSURE OVER THE WORLD

If the surface of the earth were all ocean—or all lowlands—the isobars would doubtless be arranged in belts parallel to the equator. But owing largely to the extremely complex distribution of land, of highlands and plains, these pressure *belts* are much broken up.

The seasonal changes in pressure are, of course, due primarily to the movements of the sun from tropic to tropic. Hence the average conditions are most likely to occur when the sun is over the Equator, i.e. at the equinoxes in March and September.

The pressure chart for September is indeed fairly simple, showing a high pressure area over the North Pole and extending to North Canada. Then there is a belt of low pressure along the Arctic circle, a belt of high pressure along latitude 40° N. (with maxima off California and the Azores), a belt of low pressure near the Equator, and other belts to the south, as have been described above.

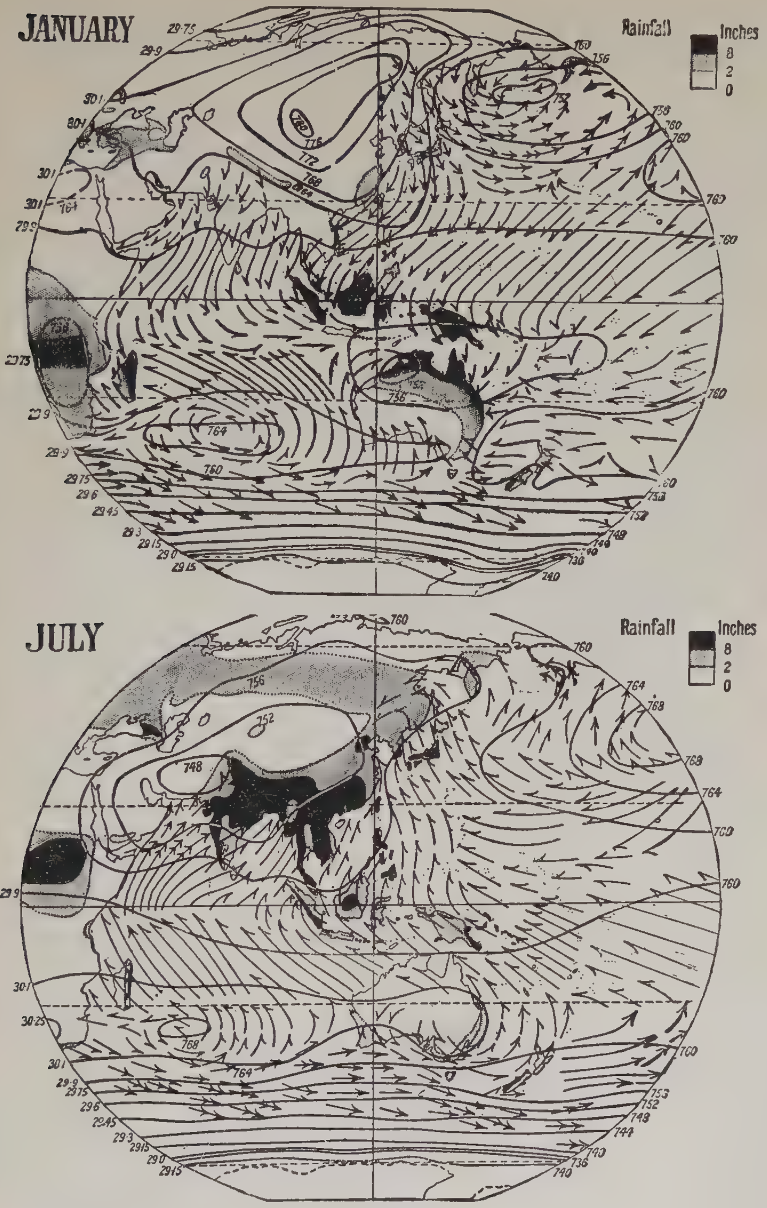
Thus in spring and autumn, when the sun is near his mean position, the actual belts resemble very closely the simple arrangement shown in Fig. 65. But great variations from this occur in summer and winter, and we can best study these from the world charts for January and July.

The great plateaux of the World are found in Thibet and Antarctica. They are much colder than the surrounding regions in winter. The warmest oceans in cool temperate regions are where the warm Gulf Stream and the analogous Kuro Siwo (off Japan) penetrate north into the polar seas. There are also areas of intense local heating *in summer* in Persia and in North Australia (see Figs. 66 and 67).

The conditions in these six regions give rise to the greatest divergencies from the normal distribution of pressure.

In July at the South Pole (see Fig. 67) there is probably an anticyclone with a pressure considerably exceeding 29·0 inches. Then near latitude 60° S. there is a belt of low pressure decreasing to 28·9 inches. The high pressure belt (in latitude 35° S.) has several foci; notably in South-east Australia, in the South Indian Ocean, and in South Africa.

The tropical belt of low pressure is centred well north of the



Figs. 66, 67. Monsoon lands. Winds, pressure and rainfall, January and July.

Equator and is very asymmetrical. It has collected about a focus in Persia, so that the 29·75 isobar (756 mm.) includes almost the whole of Asia (see Fig. 67), but is absent elsewhere in these latitudes. This disposition of the low pressure has also disturbed the high pressure belt—which is concentrated in the northern Atlantic, and the north-east Pacific.

The north polar low pressure is also absorbed by the tremendous Asiatic Low, except for a small portion near Iceland. The north polar sea has a pressure above 759 mm. (29·8), forming a well-marked anticyclonic area from which the winds blow to the south and south-east.

In January (Fig. 66) opposite conditions prevail. At the South Pole the sun is shining for 24 hours a day. Probably the pressure[1] is about 745 mm. (29·3) and does not vary very much until latitude 70° S. is approached. Then the low pressure of the Antarctic Circle (737 mm., or 29·0 inches) is reached. North of this the pressure increases steadily to the high pressure belt of 35° S. This belt is now concentrated over the seas, the land foci of Africa and South-east Australia having vanished.

The equatorial low pressure belt is well south of the Equator and is concentrated over the heated land areas, notably in North-west Australia.

The north temperate belt of high pressure is now very prominent. It extends round the world with foci in the Rockies (U.S.A.), in Spain, and in Mongolia. The latter is especially high, reaching 775 mm. (30·5 inches)—while the whole region from Morocco to Behring Straits is over 765 mm. (30·1 miles) in pressure.

The Arctic low pressure belt is concentrated near Iceland, and the Aleutian Isles (North Pacific). The Polar high pressure has shifted towards the Behring Straits and rises to 762 mm. (30 inches) near Point Barrow in Canada.

(The above descriptions will be amplified when the general circulation, the winds, the monsoons, and convection effects are studied in later chapters.)

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[1] Reduced to sea level. Actually about 19 inches.

CHAPTER VIII

WINDS AND THEIR MEASUREMENT

METEOROLOGY first became of importance in connexion with navigation, and especially as it affected sailing vessels. The advent of steamers lessened the importance of winds in commerce, but the growth of aviation bids fair to greatly increase the study of meteorological principles, especially with regard to the direction, velocity, and altitude of the winds.

WIND DIRECTIONS. Meteorologists usually use only the sixteen major directions, *north*, *north-north-east*, *north-east*, &c., to *north-north-west*, the name referring to the direction *from which* the wind arrives. (This is of course contrary to the method used in naming the currents of water in the ocean.)

Very usually the wind changes regularly in direction during the day—say from south-east in the morning, through south-south-east, south, south-south-west, and south-west in the evening (as at Perth in midsummer). This change in opposition to the apparent movement of the sun (from east through north to west) is technically called backing, while if the winds change in accord with the sun (say from north through north-west to west), it is called veering.

In the northern hemisphere winds veer from east *through south* to west in accord with the sun.

Some confusion is likely to arise in the tropics. For instance at midsummer in Darwin, the sun moves from east through south to west, as if the sun were still in the northern hemisphere. It is now overhead at the Tropic of Capricorn and well *south* of Darwin. However, the path of the sun is the criterion, and so logically ‘ veering ’ has two different meanings at Darwin (and similar places), according to the time of the year ![1]

THE WIND VANE. The direction of the wind is usually indicated by a weather vane of some such form as that shown in Fig. 68.

The arrow-head is set horizontal. The tail consists of two vertical plates fixed at an angle, which ensures steadiness. The pointers below are usually set by means of a magnetic compass in the following way.

On Fig. 69 are the lines of magnetic variation (or isogonic lines).

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[1] These definitions are official in Australia. It is quite usual, however, to define *veering* as clockwise change and *backing* as counter-clockwise change irrespective of the hemisphere. This is preferable,

If the wind vane is set up, say, at Derby, Western Australia (on the line of *no* variation), then the north-south pointer is to be made exactly parallel to the magnetic needle (see A).

At Sydney the variation is 10° E., which means that the true north (the direction to the North Pole) is 10° to the west of the magnetic needle (as at C). At Melbourne it is 8° 15′ to the *left* of the needle (looking north), and at Perth 5° to the right of the needle (as at B).

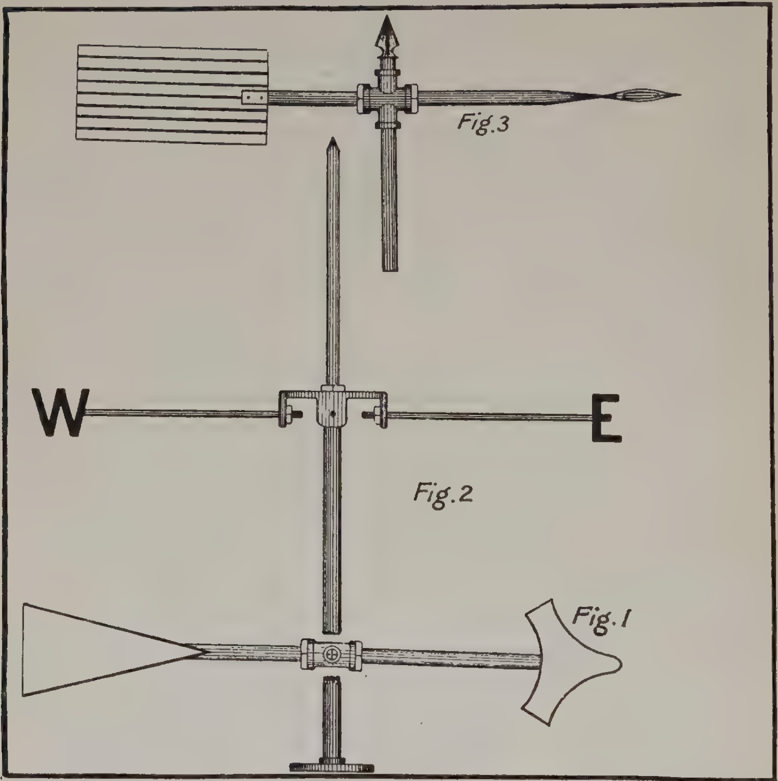

FIG. 68. Wind vane of the Australian Weather Service. Fig. 1 shows the arrow in plan. Fig. 2 shows the direction pointers fixed to the standard. Fig. 3 shows the floating head which slides over the axis. (From *Instructions to Australian Observers*).

Many elaborate instruments have been designed to give a record of wind direction. One simple but satisfactory method consists of a drum (mounted on the axis of the wind vane), on which the record is made by a pen. The latter is lowered continuously by

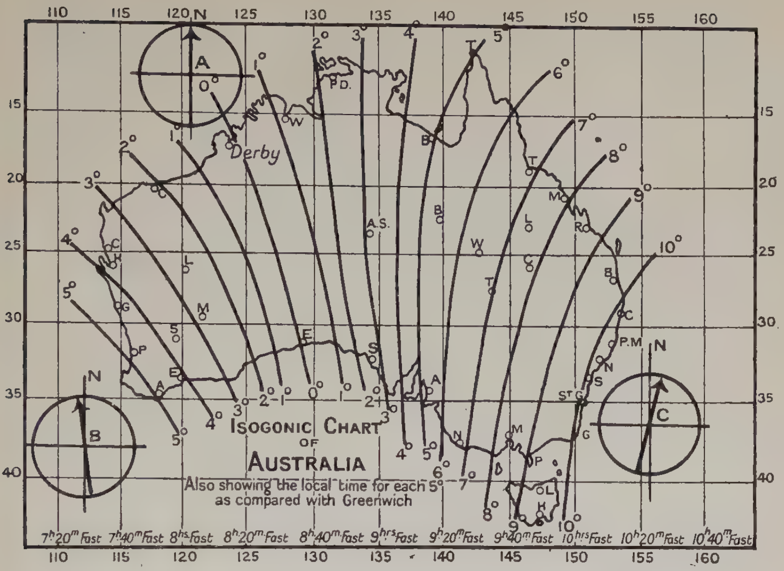

FIG. 69. Magnetic variation and local time. (From *Instructions to Australian Observers.*)

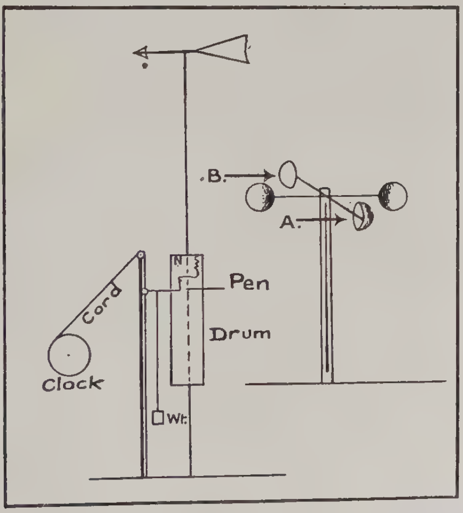

FIG. 70. The principle of the wind direction recorder (on left) and of the Robinson anemometer (on right).

a clock. In Fig. 70 the wind vane is pointing to the north and the pen is drawing a line under the portion of the record sheet labelled ‘ north ’. Previously it had been recording a north-east wind. For a south wind the opposite side of the drum would swing round and receive the pencil marks. The chart usually records for a week at a time, i. e. the pen is lowered from top to bottom in seven days.

Wind Velocity. Besides determining the direction of the wind it is of great importance to know its velocity. This is reckoned in *miles per hour* or in *metres per second,* the latter giving approximately half (or ·447) of the former. Thus 10 m. per hour equals 4·47 metres per second.

There is another relation of special interest to engineers and aviators, which relates wind velocity to the pressure or force exerted by it. This relation has been variously determined, but the formula

$$P = \cdot 003\, V^2$$

describes it very closely in pounds per square foot (P) and miles per hour (V).

As the wind velocity increases, so does the weight of objects which can be moved thereby, and a useful table is given below, in which the last column enables any one to judge the velocity of moderate winds fairly closely.

WIND VELOCITY (PARTLY AFTER MILHAM)

Name	*Miles per hour*	*Metres per second*	*Beaufort Scale*[1]	*Pounds per sq. foot*	*Objects moved (approx.)*
Calm	0	0	0	0	Smoke rises vertically.
Light air	3	1·3	1	0·03	Smoke drifts.
Light breeze	13	5·8	2	0·50	Just moves leaves.
Gentle breeze	18	8·0	3	1·0	Moves twigs and loose paper.
Moderate breeze	23	10·3	4	1·6	Raises dust, moves small branches.
Fresh breeze	28	12·5	5	2·3	Small trees, in leaf, sway.
Strong breeze	34	15·2	6	3·5	Large branches in motion.
High wind	40	18·0	7	4·8	Difficult to walk against.
Gale	48	21·5	8	6·9	Breaks twigs of trees.
Strong gale	56	25·0	9	9·5	Blows slates off.
Whole gale	65	29·0	10	12·0	Trees uprooted.
Storm	75	33·5	11	16·8	
Hurricane	90	40·0	12	24·0	

[1] According to Shaw the twelve Beaufort equivalents are 2, 5, 10, 15, 21, 27, 35, 42, 50, 59, 60, and 75 miles per hour.

Somewhat similar information is given graphically in Fig. 71. The highest velocity that can be recorded by instruments is somewhere about 120 miles per hour. Higher velocities can be calculated approximately from the displacement of damaged structures such as brick or iron chimneys, iron girders, brick walls, iron tanks, &c. In some tornadoes in America it is supposed that velocities approaching 400 miles per hour have been experienced in isolated patches.

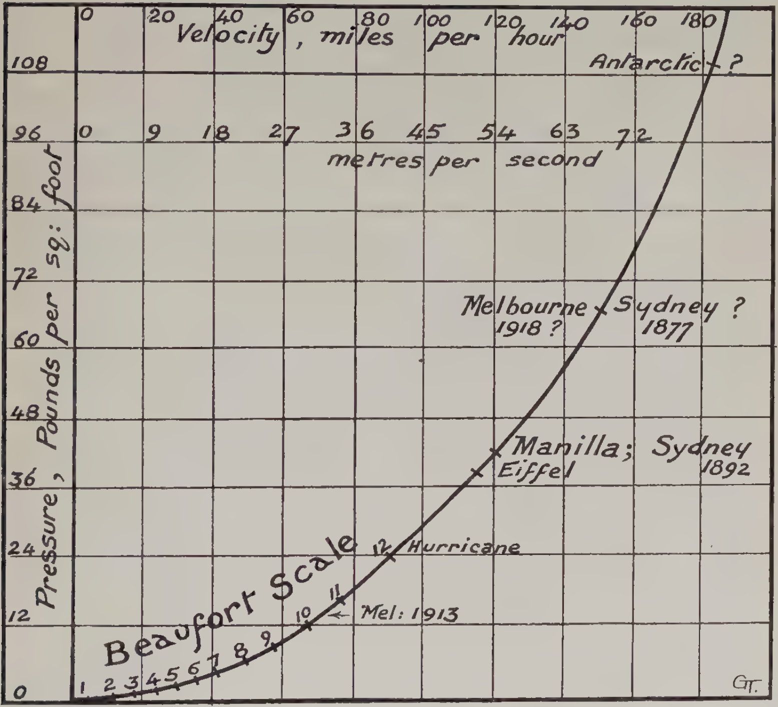

FIG. 71. Velocity and pressure of wind, showing the relation between the Beaufort Scale and the French and English scales.

Although the Brighton tornado of February 2, 1918, may have reached 150 miles per hour, the highest *officially registered* velocity in Melbourne is only 67 miles per hour. Engineering calculations show that a wind of 80 miles per hour was necessary to break the heavy chimneys destroyed in the University some few years ago.

There are two instruments commonly in use to measure wind velocity. The older Robinson anemometer (or wind-recorder) merely shows the total revolutions of a set of revolving cups up to the time of inspection. It is neither so accurate nor so instructive as the Halliwell-Dines anemometer.

The Robinson anemometer has four hemispherical cups (see Fig. 70), which are mounted on cross-arms and rotate about a vertical axis. With a wind as shown by the arrows, the front cup A will rotate to the right, and the back cup B to the left.

The concave side of the cup A opposes more resistance to the wind than does the convex side of cup B. Hence the cups move with the convex side forward, but with a velocity much less than that of the wind (see Fig. 188).

Actual experiment shows that with the usual size of instrument the wind velocity is about three times that of the cups. By a system of cogs the number of rotations can be recorded on a dial (not sketched), which is usually figured to show the distance run by the wind in miles.

It is to be noted that a calculation involving a specified *time* is always necessary to convert this distance or *mileage* into velocities.

The Robinson anemometer is usually read at 9 a.m., and the reading—subtracted from the previous day's reading—gives the miles of wind. An example will make the procedure clear.

Reading 9 a.m. Feb. 2, 1918 = 2,477·31 miles
Reading 9 a.m. Feb. 3, 1918 = 2,615·35 miles

Hence in 24 hours = 138·04 miles

The average velocity between the two readings = 5·7 miles per hour.

To obtain the velocity at any particular time, it is necessary to watch the change in the figures, say, for one minute, and then multiply by sixty.

Thus suppose in one minute the dial changed from 2,615·35 miles to 2,615·45 miles.

Hence 0·10 miles were run in one minute, and therefore 6 miles in one hour, which gives the required velocity.

The Dines Anemometer. This instrument is more direct in principle than the Robinson anemometer. A cross-section of it is shown in Fig. 72. It consists of two parts.

The 'head' is built up essentially of a metal tube which is held facing the wind by the vane. This is usually mounted on the roof of a building or on a wind tower. The moving air passes down the tube into the main portion of the instrument.

The body of the instrument is usually many feet lower, and generally within the building. The air finally rises into the interior of the floating 'bell' (see Fig. 72). Around this bell is a hollow copper float, like a life belt, which keeps it suspended in the liquid in the container.

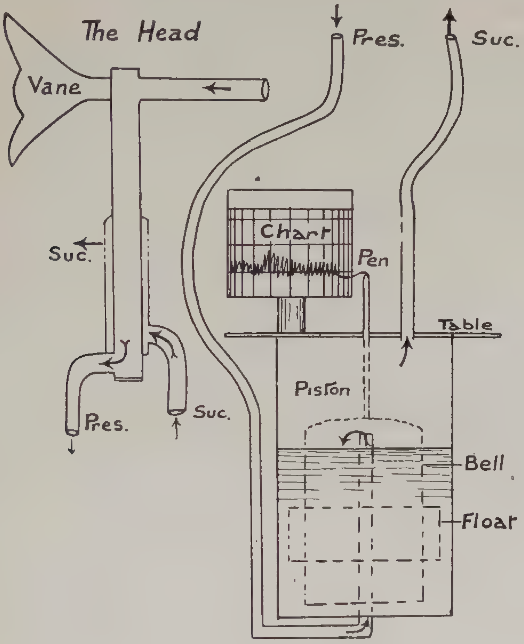

FIG. 72. Dines' pressure-tube anemometer.

As the air pressure rises and falls, so does the bell rise and fall. A piston is attached to the top of the bell and passes by an airtight gland through the table of the container. It carries a pen at its upper end. The rise and fall of the pen is recorded on a sheet attached to a rotating drum, actuated by a chronograph.

There is usually a second tube communicating with the air space immediately above the floating drum (Fig. 72). The upper end of this tube embraces the lower portion of the 'head', and is perforated so that the movement of the wind past the orifices *sucks* the air from above the float. The pressure and suction tubes therefore act together to move the float, and the combination ensures greater steadiness in the movements of the pen.

The record made (see Fig. 73) is very interesting. It shows conclusively that every wind is made up of numerous gusts, which may rise from calm to 20 or 30 miles an hour, or more, almost instantly. If the wind held steadily at 20 miles an hour, the graph would be a horizontal line, whereas it is always a broad ribbon made up of numerous vertical stripes. Each stripe represents approximately a separate gust.

If the time-scale be spread out (by running the chronograph more rapidly) it is possible to count the important fluctuations in the wind velocity. Thirty of these changes per minute are not unusual, and this 'gustiness' of the wind is of great importance in aviation.

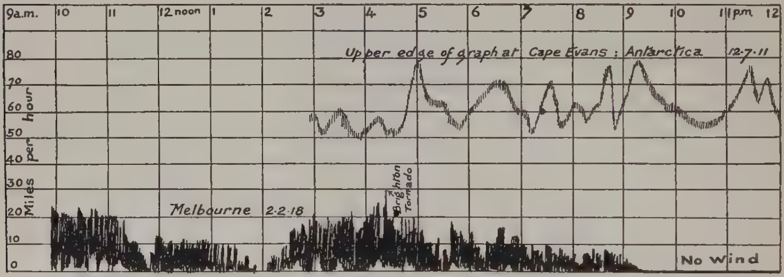

Fig. 73. Dines' anemographs showing the wind variations at the Bureau on the day of the Brighton Tornado. Above is a blizzard chart (upper edge of 'ribbon' only) recorded in Antarctica.

In Fig. 73 (at the bottom) is shown a typical graph at Melbourne on a moderately windy day. It is of special interest since on the same day at Brighton (a suburb, 6 miles south of the Weather Bureau) occurred the most destructive tornado experienced in Australia (though, of course, hurricanes have done infinitely greater damage). No evidence of this is shown in the city record, unless it be the gust reaching 30 miles an hour at about 4.30 p.m. After 9 p.m. the wind died out completely, and the pen merely drew a line along the zero of the graph.

For comparison the chart of a blizzard which I experienced at Cape Evans, Antarctica, is inserted in the upper portion of the figure. Only the *upper edge* of the wind 'ribbon' is shown. In this case the gusts rarely fell below 30 miles per hour, so that a broad ribbon was drawn on the sheet between the 30 and 60 (miles per hour) ordinates.

The Study of Wind Records

A convenient method of recording wind direction data is by means of a wind-rose. This is based on a set of eight lines, radiating from a point, which are parallel to the eight points of the compass (see Fig. 74). Along these radiating lines the required data are plotted in the appropriate directions.

The average winds for January at Melbourne (for the period 1897 to 1901) are shown in the first graph. North winds blew for 63 hours during the month, hence 63 units are measured off from the centre along the north radius. Similarly 34 hours are plotted along the north-west radius, and 111 hours along the west radius. Joining the eight points thus plotted, an irregular octagon is obtained, which is the wind-rose for January at Melbourne. Similar wind-roses are given for April, July, and October.

The wind direction is seen to vary considerably during the year. In midsummer (January) the south wind blows most frequently, followed by the south-west and west winds. The north-west, north, north-east, and east winds are almost negligible. If we refer to the average pressure map for January (Fig. 57), we see that these south winds are due to the pressure gradient at Melbourne being from south to north.

In April—which may be taken to represent autumn—the wind blows for almost equal periods of about 100 hours from south-east, south, south-west, west, and north. A great increase of north wind is evident.

In July, which is the coldest month, the wind-rose is very unsymmetrical. The north wind blows for 230 hours, whereas the south and south-west winds only blow for 100 hours each. (Here again reference to Fig. 60 will show that the gradient at Melbourne determines the average wind.)

In October, north, south, and west winds each blow about 120 hours. The one constant feature throughout the year is the absence of east winds. The winds in the periods of greatest heat and greatest cold deviate most from the average annual wind direction, as was to be expected. Hence for the study of wind direction, as in most other departments of the science, the two months of greatest variation are January and July, while April

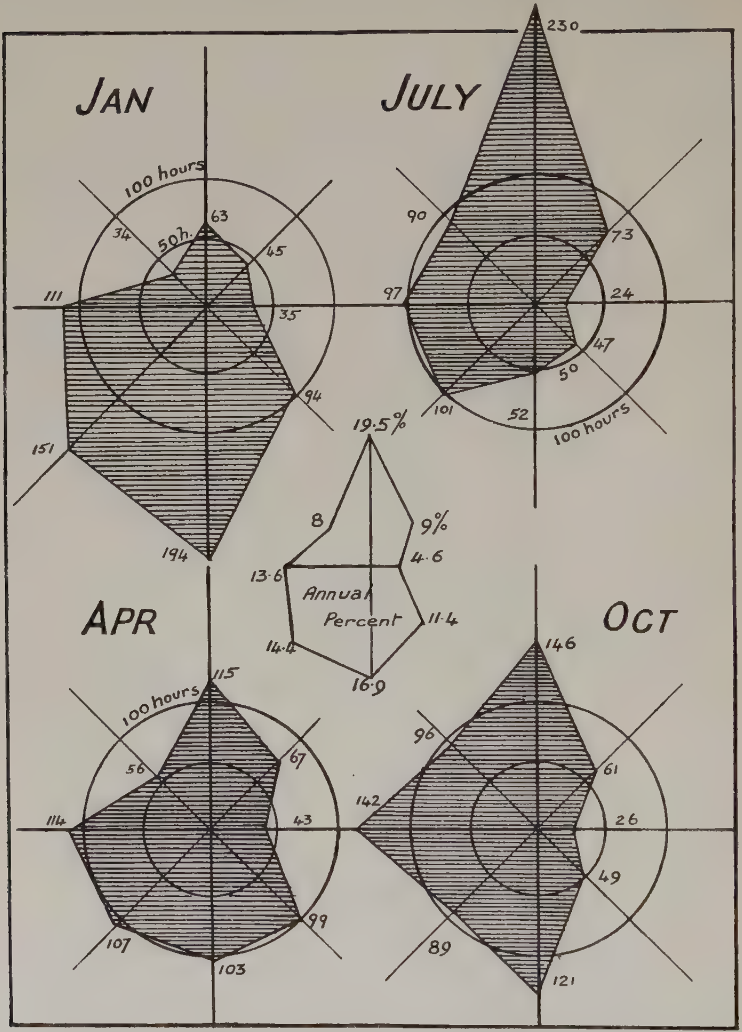

FIG. 74. Wind-roses for Melbourne. Figures represent hours of wind, except in central (annual) graph where they are percentages, based on all winds for 1897–1901.

is probably the month which approaches most nearly to the annual distribution of the wind. The latter wind-rose is given in the centre of Fig. 74.

Wind Force. The average force of the wind also varies according to the direction. The most prevalent wind (from the north) blows at 10·5 miles per hour at Melbourne. The other winds have the following velocities: south-west 9·1, south 8·6, and the rare east wind at 4·4 miles per hour.

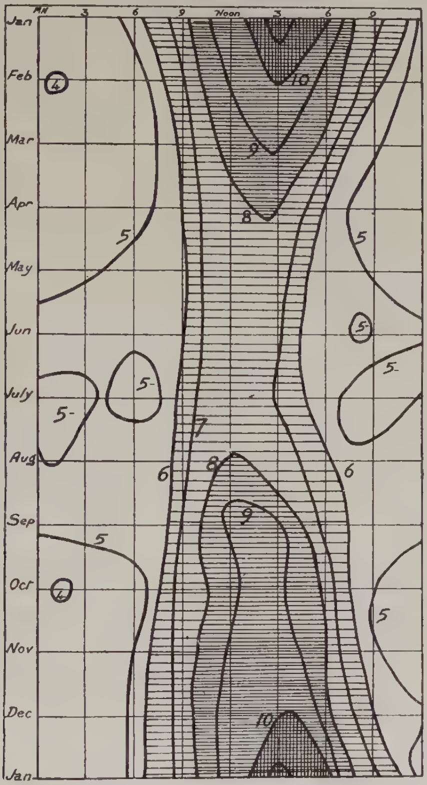

Fig. 75. Variation in wind velocities for each hour of the year at Melbourne. Note: figures show miles per hour.

Daily and Monthly Variation. There are, however, yet other important aspects of the wind, notably the variation in velocity of the wind throughout the day and the year.

This is of especial interest to aviators, and the data is given in a comprehensive manner in Fig. 75. The salient feature is that the windiest time of the day throughout the year is in the afternoon, usually about 3 p.m. It evidently agrees with the hottest time of the day, especially in summer, and indicates that the strong winds of summer are largely convection winds due to the heating of the earth's surface.

The (average) maximum wind occurs at 3 p.m. in January, and has a velocity of 11 miles an hour. Winds of 10 miles an hour usually occur about the same time in December, January, and February (see Fig. 75).

The calmest times of the year also occur in the warm months, about 1 a.m. in February and October, when the average wind is as low as 4 miles an hour.

In winter the wind force rises gradually to noon, and there is no maximum corresponding to the heat maximum at 2 p.m. The velocities are under 8 miles an hour. On the other hand, the wind during the night is perceptibly stronger in winter than in summer, as can be seen by the broadening of the 5-mile isopleth in winter (Fig. 75).

At London[1] (Kew) the wind diagram shows the same rise in the velocity up to 2 p.m., and the velocities are much the same, but the strongest winds occur in late winter, and the lightest in late summer. This is almost opposed to the seasonal distribution at Melbourne. The daily solar effect is, of course, world-wide, but the seasonal variation depends on the latitude as well as on more complicated factors, so that a close resemblance could not be expected.

Each locality in Australia has its own set of wind charts, so that it is impossible to do more than give a general account of Australian winds. They fall off in vigour from south to north, but our tropical regions, if ordinarily characterized by gentle winds, are occasionally visited by hurricanes of extreme violence. These exceptional storms are treated later in a special chapter.

Prevalent Winds around Australia

From the pilot charts a very good idea of the dominant winds can be obtained. In the twelve monthly maps shown in Fig. 76, the coastline is divided into six regions: the north, Queensland, Sydney, south, Perth, and north-west coasts respectively.

The chief winds are shown by arrows in each region, with a figure which represents the percentage of the whole winds. Thus in April on the north coast, 33 per cent. of the winds are from the east and 32 per cent. from the south-east. The other winds hereabouts are much less important. The six colder months are shown first, and the six warmer months below.

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[1] See the *Weather Map*, Napier Shaw. London Meteorological Office.

Of the six coasts the three northern are characterized by steady winds, and the three southern by variable winds. This is due to the fact that the latter lie in the path of the anticyclones for the greater part of the year. Hence the winds change from south through south-west (or south-east) to north as the Highs pass over a locality. But, even so, there are certain definite winds

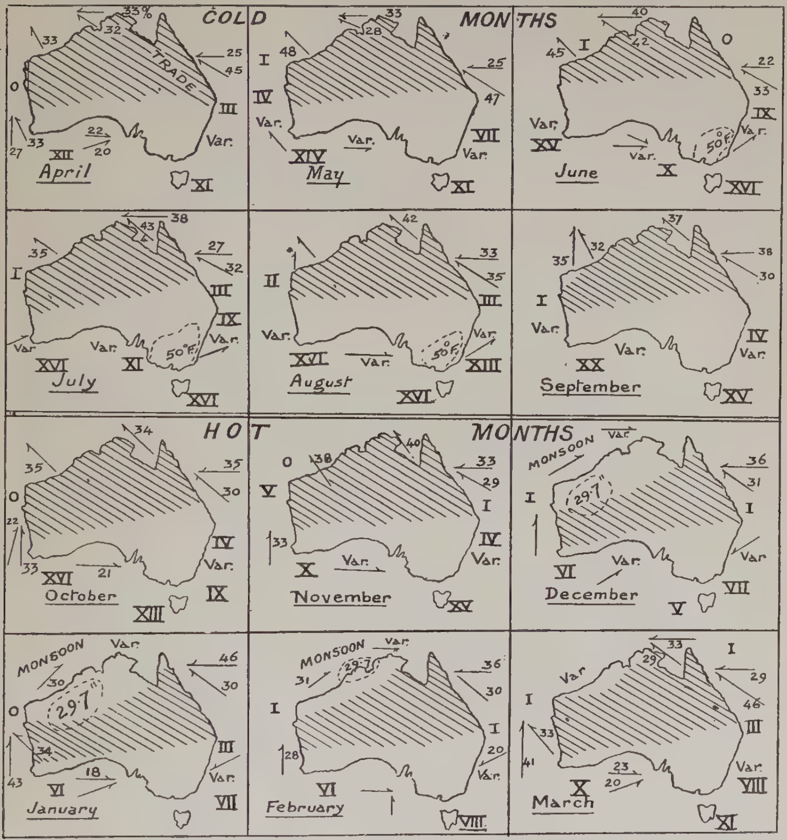

FIG. 76. Permanent winds around Australia. The figures show percentage hours of total winds along each of the six coasts. Variable winds (near the anticyclone axis) are labelled Var. The trade wind belt is shaded. Roman figures show hours (per 100 hours) in which gales blow exceeding 48 miles per hour. Data based largely on U.S.A. Pilot Charts.

which predominate in the south in some of the months, and so are worthy of mention.

1. The northern coast (from Cambridge Gulf to Cape York). It is seen that the dominant winds throughout the colder months (and indeed except in December, January, and February) are confined to the south-east or eastern quarters. During this period the sun is heating regions well to the north, and this region of steady winds is part of the trade wind belt. In midsummer (January) the north-west of Australia is strongly heated, and Lows dwell almost continuously in that region. Hence there is an indraught from the west and north-west, and the series of variable or westerly winds shown on the maps is produced. As the sun moves north again the wind changes to an easterly, and in March the south-east trade wind is again becoming important.

It should be remembered that calms are very prevalent in this region.

2. The Queensland coast (from Cape York to Brisbane) exhibits very few changes, for here are the most constant winds in Australia. Even in summer the wind merely changes from a dominant south-east to a dominant east wind.

3. The New South Wales coast. For the greater part of the year variable winds blow as the Highs pass over to the east. But during midwinter (June, July, and August) there is perhaps a preponderance of south-west winds. This is due largely to the centre of the High lying north, so that the westerly winds of the southern limb of the eddy are most abundant. Perhaps also the cold highlands to the south-west exert a local winter-monsoon effect. In midsummer there is a slight summer-monsoon effect possibly due to the heating of these same highlands. At any rate, north-east winds are most abundant among the many variable winds.

4. The southern coasts (from Cape Howe to Cape Leeuwin) are on the border line between the high-pressure belt and the region of prevailing westerlies. The centres of the Antarctic depressions (or Lows) lie considerably south of our coasts. Hence these southern coasts are controlled by the westerlies which blow between the belt of Highs and the belt of Lows. They are the most abundant winds even though the region is often traversed by south-wandering Highs or north-wandering Lows.

5. The Perth coast, from Cape Leeuwin to North-West Cape. Here the winds throughout the year blow chiefly from south and west. A southern component is more apparent during midsummer and autumn. The westerly component enters the region in winter, as the sun moves north and the southern 'prevailing westerlies' swing northwards in unison.

6. The north-west coast, from North-west Cape to Cambridge Gulf. This region agrees fairly closely with the northern region. It is dominated by the south-east trade for eight months, but during midsummer the almost permanent Low covering the hot Pilbarra region in Western Australia gives rise to a monsoon, and the coastal winds swing round from south-east to south-west. In autumn the winds are very variable, calms are common, and except for the 'willy-willies', or hurricanes, storms are rare.

The Trade Wind

The whole northern portion of Australia is at times under the influence of the south-east trades, and a *resumé* of its movements during the year is given in the following table:

Approximate Limits of the Trade Wind in Australia

Month.	*April, May.*	*June, July.*	*Aug., Sept., Oct.*	*Nov.*	*Dec., Jan., Feb.*	*Mar*
Northern limit	5° S.	0° S.	5° S.	10° S.	15° S. in east. 25° S. in west.	10° in E. 20° in W.
Southern limit	28° S.	22° S.	25° S.	28° S.	27° S. in east. 32° S. in west.	22° in E. 30° in W.

These belts are clearly shown in Fig. 76. As in every other seasonal feature, the trade winds move north and south with the sun. In midsummer their northern boundary is made somewhat irregular by the north-west Low. A comparison with the monthly rainfall belts, or better still with the solar-control model (frontispiece), shows how closely the arid areas are related to the trade winds. On the east, however, they are important rain-bringers.

One cannot repeat too often that there is rarely any discontinuity in nature's distribution of forces. Thus the steady easterly and south-east winds which we are now considering merge gradually into the easterly winds blowing along the northern margin of a High. So also the permanent westerlies merge into the westerlies blowing along the *southern* margin of the High.

As regards velocities, the trade wind of the Queensland coast blows as a 'moderate breeze' (of about 23 miles per hour) for days on end. The comparative absence of other winds is shown by the following table, where the east (NE.–SE.) winds and west (NW.–SW.) winds are given.

9 *a.m. observations* (*average* 1916 *and* 1917)	*Jan.*		*Feb.*		*Mar.*		*April.*		*May.*		*June.*		*July.*		*Aug.*		*Sept.*		*Oct.*		*Nov.*		*Dec.*		*Per cent.*	
	E.	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*	*E.*	*W.*
Grassy Hill, Cooktown	21	8	18	11	21	4	27	2	28	2	29	1	30	1	30	1	28	1	26	1	24	4	19	8	83	12
Thursday Island, Q.	11	12	13	11	13	18	27	2	30	0	30	0	31	0	31	0	29	0	29	1	20	4	10	15	75	17

GALES AROUND AUSTRALIA. There are few gales in the trade wind area, but they increase in number as we proceed south. The percentage of hours of gales (force 8) in each 100 hours is shown on the twelve maps in Fig. 76. South of Leeuwin are the stormiest waters near Australia. In September gales blow for one-fifth of the month in this area. During the period May to October gales occur for fifteen hours out of every hundred. Midsummer is the calmest period, when the Roaring Forties have moved south, for only 6 per cent. of the hours experience gale strength. Similar storm periods occur in Tasmanian waters. Off Sydney, June and July have gales for 9 per cent. of the time, and here again midsummer gives the calmest period as regards regular gales.

CHAPTER IX

CONVECTION AND PRESSURE GRADIENT

Convection and Sprung's Experiment. It is advisable before describing the general wind circulation of the globe to consider what is implied by Convection and Pressure Gradient.

Convection of heat (unlike conduction) involves the actual movement of the body giving off heat. In meteorology we are principally concerned with the movement of heated air, whereby other cool portions of air are gradually warmed by the warm current.

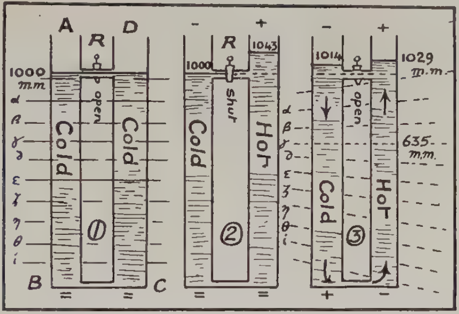

Fig. 77. Pressures and circulation of a heated fluid. Water-jackets omitted (after Sprung). The Greek letters show approximately the planes of equal pressure.

If the temperature of the earth and of the atmosphere were everywhere the same at similar levels, there would be no reason for movement of air from one region to another, and there would be no wind.

The method by which changing temperatures affect the pressure and circulation of fluid is best studied by an experiment made by Sprung.

Two vertical glass tubes, AB and CD (about 1,000 millimetres long), are joined below by a horizontal tube BC, and near the top by another (see Fig. 77). The latter can be closed by a tap at R. These vertical tubes are enclosed in water-jackets, which can be filled with water at a definite temperature.

To commence with, the whole system of tubes is filled with water at 10° C. The water stands 1 metre high in each. Now close the tap R, and heat the jacket of D C to a temperature of 100° C. by circulating boiling water or steam through it. Keep A B cool by circulating water at 10° C. around it. We shall find that the heated column has expanded to 1,043 millimetres, while the cool column remains at 1,000 millimetres (see No. 2 in Fig. 77).

The pressures at B and C are still equal, for the mass of the water is not changed. But the density of the water in D C is now less than that in A B. Consequently the pressure at equal levels is only the same at the bottom of the two tubes, and is slightly greater in C D elsewhere *at the same level.* For instance, at one metre above the bottom the pressure is nothing in A B, but is that due to 43 mm. of water in C D.

Now open the tap R, keeping the temperature conditions as before. The water moves from D to A, and the pressure diminishes in column C D in consequence, while it of course increases in column A B.

At the bottom of the columns the pressure is now greater on B than on C, and a flow takes place toward C D. Finally the circulation will reach a steady velocity and will continue as long as the temperature differences remain the same.

When this occurs the level is not the same in the two columns. In the warm column it stands at 1,029 millimetres, and in the cold column at 1,014 millimetres above the bottom plane.

Let us now consider how the pressures have altered.

1,000 mm. at 10° F. weigh same as 1,043 mm. at 100° F. (by experiment).
And 987 mm. at 10° F. weigh same as 1,029 mm. at 100° F. (by calculation).

Hence 987 mm. in the left-hand column would balance the water in the right column. There is therefore an excess of 27 millimetres in the cold column. Hence the pressure *at the base of* the cold column is now in excess, or positive, and is less (or negative) in the other column at the same level.

Above the metre level we find that the hot section (29 mm. high) is considerably heavier than the cold section (14 mm. high). So that the positive pressure is here on the right, and the relation is just opposite to that at the base.

Obviously at intermediate points these differences of pressure must get smaller and smaller until, at the 635 mm. level, the weights are the same in the upper portions of both columns (or 379 mm. at 10° C. equals 394 mm. at 100°, which can readily be shown).

Hence the result of warming one column of fluid has been to alter the position of the lines of equal pressure. These are shown roughly by the Greek letters in Fig. 77, and they correspond to what we call isobars in the air. There is in our atmosphere no method of heating resembling the water-jacket, but some such circulation is set up by convection and conduction between warmer and cooler portions of the earth's surface.

In our atmosphere the distances between the columns are usually very great and their heights relatively small. For instance, the heated column at the equator may be only 4 or 5 miles high, while the cool column (so far as it exists) is probably 3,000 miles away in latitude 40°. But the bulging of the isobars over the equator due to convection certainly occurs, and the equilibrium of the air is disturbed in much the same way as in the experiment, so that the air moves in each plane from high pressures to low pressures. Smaller convection effects arise locally and give rise to the ' pockets and bumps ' of the aviator, as we shall see later. But all these air currents are due to pressure changes arising from differences in temperature. They have been described and measured somewhat as follows :

VERTICAL AIR CURRENTS. It is difficult to devise an instrument which will sort out the vertical component only of the air movement. Several attempts have been made by Dechevrens and others, while J. S. Dines has obtained valuable data from *ballons sondes.*

Dechevrens in the Isle of Jersey with a fan anemometer 50 metres above the ground found ascending currents of the order of 1·8 miles per hour throughout the day. They varied from 1·7 at 4 a.m. to 1·9 at 1 p.m. Descending currents were of a very feeble character, varying from 34 *metres per hour* at 4 a.m. to 130 *metres per hour* at 3 p.m.

Dines found that with small balloons (12 grams) a rate of ascent through the air of 2·3 metres per sec. (5 miles an hour) can be safely assumed. From this he deduces the following figures for vertical currents.

The eight ascents showing vertical velocities over 1 metre per sec. (2·4 miles per hour) occurred mainly on days of strong wind, and vice versa. The strength of the vertical currents at 1 p.m. is nearly double that at 4 p.m.

Down currents reaching nearly 3 metres per second were occasionally met with in the first kilometre of ascent. The strongest vertical circulation was found with a sky partially covered with cloud. Although an absence of cloud is favourable to the production of convection currents due to solar heating of the ground, yet the convection currents when formed tend to produce cloud in their turn and so cease to be associated with a clear sky.

Pressure Gradient. In much the same way that the velocity of water depends on the gradient or slope of the land surface, so does the velocity of the air current (or wind) depend on the slope of the isobaric surface.

The amount of the descent of the barometer in a horizontal distance of one geographical degree (69 statute, or 60 nautical, miles) is used as the measure of the gradient.

In Fig. 78 the distance from Geraldton to Hobart is about 2,000 miles, or 30 geographical degrees. The barometer falls from 30·2 inches to 29·0 inches in this distance, or 1·2 inches in 30°.

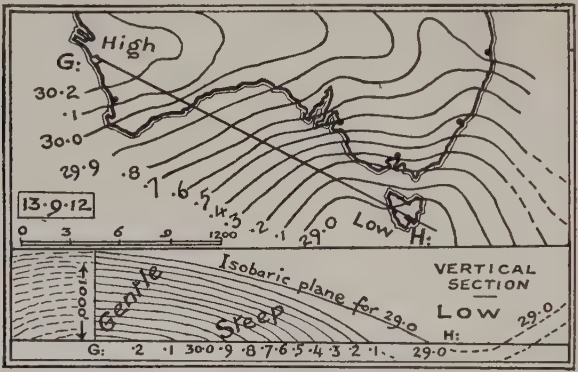

Fig. 78. Chart and vertical section for 13 September, 1912, illustrating a very steep gradient half-way between Geraldton and Hobart, and a gentle gradient near Geraldton.

The gradient (per degree) is therefore 0·04 inches. (Theoretically, the line of section in Fig. 78 should cut the isobars at right angles. This is nearly true for most of the section.)

In England the unit of distance is 15 nautical miles (or one quarter of a degree), and the gradient—on this scale—is 0·01 inch (of mercury per 15 nautical miles).

Actual Slope. The isobaric surfaces are of course real, if invisible, and their slopes are easily determinable from the weather map.

Suppose (in Fig. 79) isobar 29·0 inches (at A) is 695 miles (or 10 degrees) away from isobar 30·0 inches (at B). This represents a gradient of 0·1 of an inch, as we have seen. We shall reach the isobaric surface of 29·0 at C, about 950 feet *above the earth* at B. A vertical section to true scale (similar to that in Fig. 79) would show a triangle with a base AB of 695 × 5,280 feet, and altitude BC of 950 feet. Hence

$$\tan A = \frac{950}{3645250} = \frac{1}{3850}.$$

Hence, even with this steep barometric gradient, the slope is very slight indeed, about 1·3 feet in a mile.

The vertical section in Fig. 78 shows that where the warped isobaric surfaces are steep, their edges (the isobars) are crowded on the plan, and where the surfaces are nearly level their edges are shown far apart on the plan. Hence the air currents are strongest where the isobars are crowded.

It is not difficult to deduce approximate relations between wind velocity and gradient.

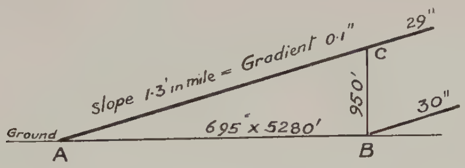

FIG. 79. Vertical Section (not to scale) illustrating the actual slope of an isobaric surface of gradient 0·1 (AC).

Thus Whipple gives the following figures as applying to Kew.

Gradient per ·25 degree.	*Gradient per degree.*	*Wind Velocity.*
·002 inches	·008	5·0 miles per hour
·010 ,,	·040	9·2 ,, ,,
·020 ,,	·080	16·5 ,, ,,
·030 ,,	·120	25·5 ,, ,,

The relation, however, varies considerably with the latitude; and also with the local conditions affecting the instrument, such as aspect, height, topography, and obstructions.

GRADIENT WINDS. Gold gives accurate figures for the theoretical or gradient winds (as calculated from dynamical considerations) related to various distances between the isobars (as usually plotted).

DISTANCE APART OF $\frac{1}{10}$-INCH ISOBARS (IN MILES)

	Velocity in miles per hour of gradient wind											
	3	*8*	*13*	*18*	*24*	*31*	*38*	*46*	*55*	*64*	*75*	*100*
Lat. 30°	1,750	650	425	293	218	168	137	112	100	81	69	52
,, 40°	1,370	505	310	225	168	130	105	87	75	62	54	40
,, 50°	1,190	425	262	187	144	122	87	75	62	53	46	34

Hence in our latitude (30° S.) if the barometer reads 29·9 inches at A and 30·0 inches at B, and these places are 218 miles apart, then the wind will theoretically be 24 miles per hour. If the distance between two adjacent isobars is 1,750 miles, it represents a wind only of 3 miles per hour; if 55 miles apart it means a velocity of 100 miles per hour.

It is very important to note that these winds are never experienced at the surface with these isobaric distances. Surface friction, convection, &c., reduce the speed by 50 per cent. Thus Gold shows that at Berlin the following relation obtained in 1905:

	Summer.	*Winter.*	*Year.*
Mean surface wind	10·5	11	10·8
Gradient wind, as calculated	19·7	26	23
Actual wind at 1,000 metres	18	24·5	21

Several practical points arise in connexion with this question. Obviously surface winds do not represent the whole circulation due to the atmospheric 'engine'. Its energy is damped or thwarted by the rough surface of the earth. Secondly, we find that this frictional effect dies out before we reach 3,000 feet (1,000 metres) above the earth. Thirdly, we can calculate from the surface isobars what the gradient wind will be at about 1,000 metres, and so prepare aviators for what they may reasonably expect at their normal flying levels of two or three thousand feet.

An account of the way in which the wind increases in velocity with height—with reasons therefor—will be found in the chapter dealing with Aviation and Meteorology.

CHAPTER X

FERREL'S LAW

Theories of Circulation. The last ten years or so have witnessed an almost complete alteration in regard to the theories of the general circulation of winds among the bulk of meteorologists.

Meteorology, though based upon natural laws as truly as physics or astronomy, has lacked all the definiteness associated with those sciences. For years one of the main objects of the study of meteorology has been the forecasting of weather, but the period involved has not yet been extended with any certainty beyond two or three days. Seasonal forecasting, which would practically nullify the damage by floods or droughts, is still quite beyond the powers of the scientific observer except in one or two favoured regions. The ambiguous long-distance predictions of the amateur weather prophet, based on the position of the moon, or the planets, &c., are utterly discredited by all competent critics.

Further than this, the more deeply the structure of some of the commonest features of our weather is investigated the less does it corroborate the early explanations. Thus it is found that the upper air in a Low is warmer (and not as believed cooler) than that of the surrounding air. It is found that the air as a whole gets warmer and not cooler above a certain level. Many other instances could be given, but they would only emphasize the poverty of our knowledge.

It has been stated that the attitude of a meteorologist to the general study of the ocean of air is much the same as that of 'a minnow living behind a stone in a big river, wildly excited over every eddy and paying more attention to them than to the river as a whole'. This caustic criticism is not really applicable now that the investigations of Teisserenc de Bort, Rotch, Dines, Shaw, Gold, Cave, and others, have directed the attention of meteorologists away from surface conditions to those obtaining in less confused regions of the atmosphere.

One result of this new flood of light has been that less prominence is assigned to the part played by direct heating in promoting circulation, and more to the dynamical factors due to the rapid rotation of the earth and to the inertia of the moving air itself.

Movement on a Sphere. It is necessary to consider one or two simple dynamical problems before we proceed to study the actual distribution of the chief winds of the earth.

The simple rules of velocity and direction with which the layman is familiar usually assume that any moving body (such as a man or a stone or a bullet) is changing its position on a *fixed* surface—the earth. If the body is moving in a straight line it will continue to do so until some force deflects it or stops it. The same law holds good with regard to winds blowing across large portions of the earth. But the earth has a tremendous angular

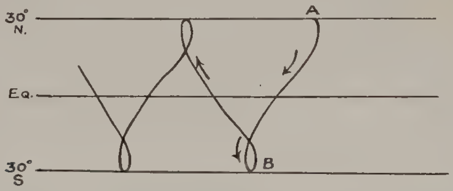

Fig. 80. The path of a body projected due east on a rotating sphere with a velocity of 80 miles an hour. (From Cordeiro.)

velocity of its own about its axis, so that a point on the equator moves from west to east at 1,037 miles per hour. At Melbourne a point moves to the east 818 miles per hour, and at the poles this rotational velocity is of course zero. Hence a body projected over a rotating sphere with such a speed describes a very different path (as traced on the sphere) from what it would have over a limitless fixed plane.

A concrete example (due to Cordeiro) will show what would occur.[1]

Suppose a body is projected due east from a point on a true sphere (rotating like the earth) in 30° N. lat. with a velocity of 80 miles per hour. (Its *absolute* velocity in space is 80+898 miles to the east). It will curve to the right immediately and move south—approaching the equator, and will cross the equator with a westward velocity of 190 miles in a direction W. 68° S. It will continue south, gradually turning to the *left* in the southern hemisphere until it forms a loop at latitude 30° S. and returns to the equator as shown in Fig. 80, and finally to latitude 30° N. again.

The above example will show that the dynamical laws are much more complicated when applied to a rotating sphere, than when a fixed plane is in question.

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[1] *The Atmosphere*, Cordeiro, New York, 1910.

However, by means of simple models and illustrations a fair knowledge of the principles involved can readily be gained.

Ferrel's Law. If we mount a hollow metal sphere on a vertical axis, so that it can be rapidly rotated, we can reproduce some of the conditions which determine the path of air currents over the globe. A funnel can be soldered to the sphere (which may be about two feet in diameter) above and directly in line with the axis (see Fig. 81).

If now melted pitch be poured into the funnel when the sphere is at rest, it will of course flow over the surface of the sphere in the direction shown by the arrow at *a*. If now the sphere be rotated rapidly in the direction shown by the arrow *b*, then the melted pitch will follow the path *c*. In other words, it will curve round to the right. If we were to squirt pitch up from the south pole it would take the path *d*, under the same conditions showing a deflection to the left.

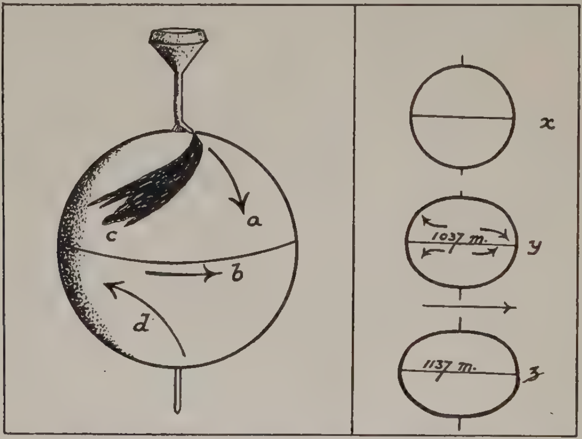
The reason for these deflections is seen if we consider the relation between the velocity of the pitch and the velocity of the surface which it is just flowing over. The pitch starts at the axis with no rotational velocity (to the east) and gradually reaches surfaces having greater and greater velocity. Hence it is always being *left behind*; for its own velocity to the equator is only *gradually* affected by the rotational velocity of the surface it is flowing over.

In the same way, pitch flowing poleward from the equator reaches regions of less and less rotational velocity; and so its inherent eastward velocity makes it overreach the earth's surface and get ahead of it. A body moving from the equator towards the pole in the northern hemisphere deviates to the north-east (i.e. to the right), and in the southern hemisphere moves to the south-east (or left).

The Lesson from the Shape of the Earth. The proof as applied to bodies moving directly to the east or west is not so obvious. Yet much light may be thrown on it indirectly by considering the origin of the shape of the earth. Originally, perhaps, the earth was a true sphere (as at Fig. 82, *x*), but owing to its great rotational velocity it has become an oblate spheroid with a polar diameter 27 miles shorter than the equatorial diameter. Fig. 82, *y*, may be taken to represent this spheroid, whose shape is determined by the equatorial velocity of 1,037 miles per hour. If the earth were to rotate more rapidly still, so that a point at the equator moved to the east at, say, 1,137 miles an hour, then the bulge at the equator would increase, and we can represent the result by *z* (Fig. 82).

Hence the spheroid *y* is only in equilibrium if the matter near the equator is moving about 1,000 miles per hour.

If we imagine a west wind blowing near the equator at 100 miles an hour, its *absolute* velocity (i. e. as compared with some stationary standard right away from the earth) is about 1,100 miles per hour. It is moving to the east more rapidly than the earth, and so is not in equilibrium with the earth's rotation. In effect we may think of it as tending to form a bulge at the equator (as in Fig. 82, *z*). Hence it moves equatorward.



Figs. 81, 82. Illustrating Ferrel's law. (Fig. 81 after David.)

If it is in the northern hemisphere this west wind tends to move to the right; if in the southern hemisphere it tends to move to the left.

The converse also holds. If the wind near the equator is blowing from the east at 100 miles an hour, it is contrary to the earth's rotation, and has an *absolute* velocity of 900 miles (1,000 *minus* 100) an hour to the *west*. Hence it is out of equilibrium with the earth as rotating at present, but would be in harmony with a spheroid with less of a bulge.

Consequently we may think of it as tending to move poleward in each hemisphere. Thus the east wind turns to the right in the northern and to the left in the southern hemisphere.

Hence we get the general law which is due to Ferrel.

All bodies moving in the southern hemisphere tend to deviate to the left, and in the northern hemisphere to the right.

Many people will have the small amount of mathematical knowledge which is necessary to understand the following explanation.

THE DYNAMICS OF THE PROBLEM.[1] With an oblate spheroid, such as the earth, the forces acting on a mobile particle (such as a mass of air) can be estimated with some approach to exactness as follows (see Fig. 83).

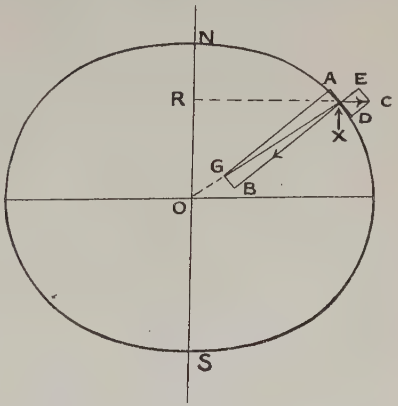


FIG. 83. Ferrel's law. The particle at x is acted on by two forces. x g is the gravitational force (not at right angles to the surface). x c is the centrifugal force, for x is rotating about the point r. If the particle is at rest, then the component x d must equal the component x a.

Any particle, as at x, is subjected to the force of gravity and to the centrifugal force due to the earth's rotation.

Since the earth is not a sphere the force of gravity does not act exactly at right angles to the surface. We may represent its direction by x o and its strength by the length x g.

By the physical law of the Parallelogram of Forces we can (under certain conditions) replace any force (such as x g) by two others at right angles to each other.

Let us choose one direction perpendicular to the surface at x and the other tangent to it. Here x a and x b build up a parallelogram with x o and can replace it, as far as its effect on the particle x is concerned.

Now x b (by definition) is at right angles to the ground and only holds the particle to the surface. But x a obviously tends to move the particle 'down the slope' towards the pole (Fig. 83).

The centrifugal force due to rotation acts at right angles to the axis of rotation; and X rotates about the point R. This force X C (outwards) can be replaced by X D and X E. Of these X E merely tends to lift the particle up from the earth, and is nullified by the immensely greater downward force X B. But X D tends to move the particle along the surface to the equator.

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[1] For a lucid account of this and allied problems see Lake's *Physical Geography*, 1915.

Hence with things in equilibrium—as the earth is at present—X A must just balance X D. It is the adjustment by these forces which has moulded the earth to its present shape.

Now suppose that the particle at X (Fig. 83) is a mass of air which is constrained (e.g. by some pressure gradient) to move to the west. Its gravity factor does not alter, but it is now rotating about R at a quicker rate. Hence its centrifugal force (X C) is increased, and the component X D is correspondingly increased. So that X D now overbalances X A and the mass of air moves gradually equatorward. In other words, it is deflected to the right.

If the mass of air is moved to the east, its centrifugal force is decreased about R. Hence X D becomes less than X A and the air moves poleward, i.e. to the right.

BODIES MOVING OVER GLOBE. It is not difficult to plot the paths which freely-moving bodies (such as air) would follow *with respect to the earth* in various latitudes. Cordeiro has given figures for moving air in northern latitude which I have transferred to the southern regions (Fig. 84). If the air were moving to the west at 80 miles per hour from Cape York, it would follow the path shown at *a*. It would curve *to the left* and describe a loop, recurving about latitude 25° S. and so continue (oscillating between 10° S. and 25° S.) around the world.

If the body of air were moving to the *east* from Cape York at some speed over 16 miles per hour, it would follow the track shown at *b*. It would curve *to the left* and reach the equator. Then continuing north it would now curve *to the right* and reach latitude 10° N. Here it would recurve and ultimately reach latitude 10° S. again. This path very well illustrates Ferrel's Law as applied to both hemispheres. If the velocity is less than 16 miles per hour the air will not cross the equator, but will follow some such path as at *c*. In the special case of air moving at precisely 16 miles per hour, it will reach the equator and then move *along it* to the west as at *d*. For starting-points in other latitudes the paths will be different of course, but will obey the same rules.

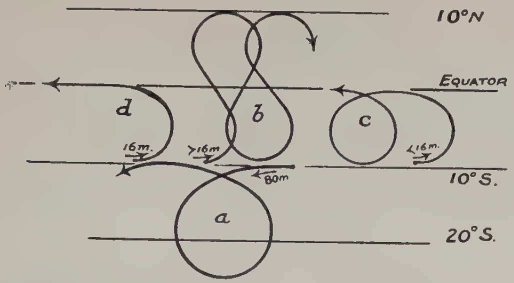

FIG. 84. Theoretical paths for moving bodies starting from Cape York at varying velocities (after Cordeiro).

Usually convection due to heating by the earth's surface and friction due to surface obstructions prevent these air-paths from remaining regular for any length of time. But occasionally they seem to be traceable in the weather charts. An example which seems to fit very closely occurred in February and March 1918 off the Queensland coast (see Fig. 85). Here a cyclonic eddy moving as a whole at about 10 miles per hour seems to have preserved its identity for a fortnight, and its track is seen to resemble that illustrated at *c* in Fig. 84. It was accompanied by heavy rains; for instance, 10½ inches fell at Sandy Cape on the 3rd, 4th, and 5th; 16½ inches fell at Cardwell on the 10th and 11th, and before it died away in the interior it gave 3 inches on the 12th to places around Winton.

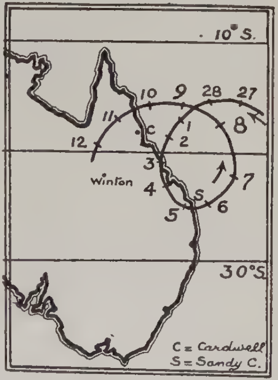

FIG. 85. Path of cyclone on Queensland coast in February and March 1918, which appears to illustrate Ferrel's law. Figures are dates.

It is helpful to remember that Ferrel's law applies to all moving bodies, to cannon balls as much as air; and even, it is asserted, to rivers. In flat alluvial it is claimed that rivers (in the northern hemisphere) have a tendency to curve to the right.

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CHAPTER XI

WINDS OF THE GLOBE

Though it is true that dynamical laws control the wind directions, yet the distribution of heat over the earth is the prime factor in originating the circulation. The hot equatorial belt and the two polar regions build up a very powerful 'twin' heat engine which operates very much like the furnace in a primitive coal mine.

To ventilate a coal mine there are two shafts—the upcast and the downcast (see Fig. 86). A furnace was lit below the upcast, and this warmed the air in the shaft above. The air expanded, and so became lighter than the air in the mine and in the downcast shaft. The heavier air thereupon displaced the lighter, which was pushed up the upcast shaft. In this way a continuous supply of air was ensured in the mine. In the world circulation the air is in general rising over the 'heat equator' and sinking over the cold polar areas, and a similar circulation is set up over the earth. The great trade wind current corresponds to the cool air moving toward the furnace.

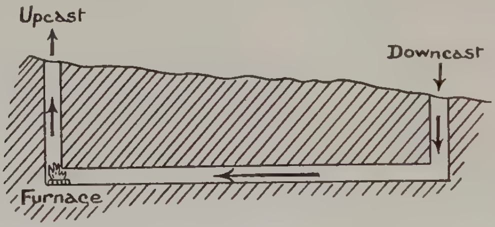

Fig. 86. Ventilation in a primitive coal mine. The upcast represents the hot equatorial region.

General Circulation

If we consider the dominant winds of the earth's surface we find that speaking generally they fall into two or three groups.

Half the earth's surface—between 30° N. latitude and 30° S. latitude—is controlled by the trade winds which blow equatorward. The remaining portions are chiefly affected by *westerly* (not northerly) winds. At the south pole (and probably the north pole) the winds are largely equatorward also.

Hence the return poleward winds which complete the circulation must be largely confined to regions above the earth, of which we have not such detailed knowledge.

In Fig. 87 such a circulation—which agrees fairly with observed facts—is illustrated at the left of the globe (as it would appear in section). In the southern hemisphere we see the trade winds commencing near H and blowing along the surface to the equator. Here the air rises to considerable heights and flows on the whole poleward. This stream of poleward air undoubtedly divides, and while some may reach the pole at S, considerable quantities descend at H and especially south of H between latitudes 30° and 60°.

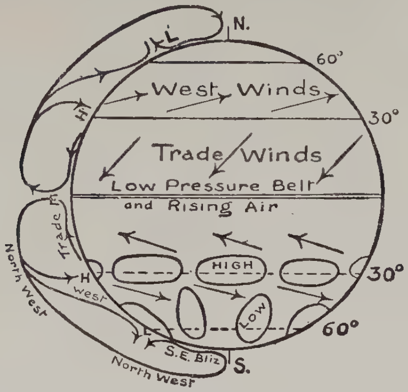

FIG. 87. Chief features of the circulation on a rotating globe. On the left the winds are shown in elevation.

In all these cases the winds of the southern hemisphere are gradually deflected to the left as explained previously, so that the trade wind blows from the south-east. The upper countercurrent (or anti-trade) changes from a north wind near the equator to a north-west and finally to a west or even a south-west wind in latitude 40°, where a large portion has sunk to the earth's surface.

Surface winds around the Antarctic and on the latter continent are chiefly from the south-east, where they constitute the famous blizzard winds (see Fig. 88). There is a permanent region of high pressure at the south pole, and the winds blowing from the pole to the low-pressure belt at 66° S. follow the same rules as does the trade wind. One might therefore with some reason term the dominant south-easters of Antarctica the ‘ polar trade winds ’.

The Pressure Belts bounding the Temperate Zone

The main principles determining the general circulation have now been described. But two very important breaks occur in the continuity of the circulation, and the phenomena associated with these ‘ breaks ’ are of vital importance in connexion with the climate and weather of temperate regions.

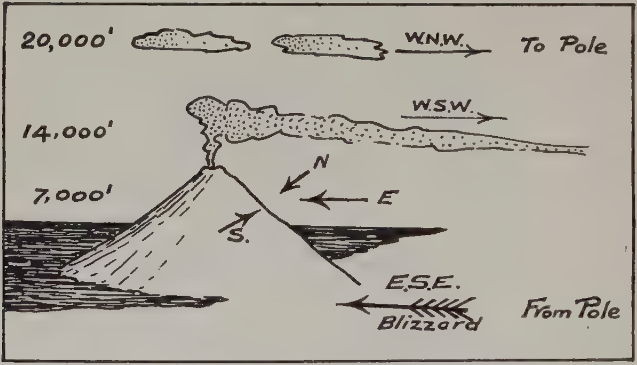

Fig. 88. Four wind layers at Mount Erebus (a volcano of 13,300 feet) at 78° S. lat. in Antarctica. (Looking north to the open sea.)

In Fig. 65 the seven pressure belts are illustrated. Three of these—the equatorial and polar areas—are mainly of thermal origin. The former is due to the heating and expansion of the air giving a low-pressure belt at the surface. The two latter are due to the intense cooling of the air at the poles—so that (at the south pole at any rate) a permanent high-pressure area occurs where the air is chilled and sinks to the surface.

The other four belts, each occurring just north or south of one of the two temperate zones, are, however, due largely to dynamic causes which must now be considered.

The overflow body of air constituting the current from the equator to the pole is subjected to several forces. There is a pressure gradient driving the air directly to the pole; just as in Sprung's experiment (Fig. 77) the expanded fluid was transferred from the warmer region to the cooler.

There is also the deflecting force due to Ferrel's law, which in the southern hemisphere deflects the equatorial overflow to the left. The amount of change is proportional to the time and to the sine of the latitude.

As Dines says,[1] 'The change of direction in one hour is given in degrees by the expression 15 sin ϕ. Thus in latitude 45°, since sin 45° = 0·71, the change per hour is $10\frac{1}{2}°$; and in a little under 9 hours suffices to turn an east wind in the southern hemisphere into a north wind.

'Suppose, then, that a place, A,[2] lies north of place B, and that for some reason the barometer at B is lower than at A. The natural result is that air flows from A to B, that is to say there is a north wind blowing over the country between A and B, but in nine hours' time the earth's rotation has shifted this north wind into an east wind.

'But as soon as any east appears in the wind, it is ceasing to move freely, since the pressure gradient is turning it back to the south, and as soon as it becomes a true east wind the pressure gradient exactly opposes the tendency to turn to the right, and we find in practice a steady east wind blowing *across* the line A B' [and parallel to the isobars].

'In recent years it has become a common practice to observe the upper winds by means of pilot balloons, and it is a fact well established by observation that within the limits given by the probable errors of observation, the wind at a height of one or two thousand feet is always blowing at right angles to the pressure gradient, and that its velocity is proportional to the steepness of the gradient and has the value that is theoretically required.'

Since the Ferrel effect diminishes when free movement is restrained, it is strongly affected by surface friction and even by the viscosity of the air. As a matter of fact even the free upper air moves to the south-east and not strictly to the east, as the poleward gradient would demand. Probably the upper current forms a spiral around the earth, gradually reaching the poles and then returning to the equator by less definite intermediate paths.

This is illustrated in a highly generalized form in Fig. 89. Here we may follow the path of one small portion of the vast upper-air spiral drift. It rises from the surface at the equator, moves to the north-east—keeping at high levels (say two or three miles up) until, near the North Pole, it descends into the intermediate layers.

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[1] W. H. Dines, *Monthly Weather Review*, U.S.A., November 1915, p. 551.
[2] This example is for the Northern Hemisphere.

Here it returns equatorward ; probably being dragged to the east somewhat by the upper and surface drifts in these latitudes. It may gradually descend to the surface and so reach the equator as part of the north-east trade wind. This is of course only one of many possible paths, but it illustrates the main features of the upper and intermediate wind layers.

The Wash-basin Analogue. It is now time to consider the origin of the belts of high and low pressure which control the surface winds in temperate regions.

If a mass of fluid in a vessel be rotated rapidly it will move away from the axis of rotation, as in the familiar experiment of whirling a bucket of water. Perhaps a better parallel is seen when a wash-basin is emptied. The water starts quietly to pour out by the central hole, but soon a rotational movement is set up, and finally a deep hollow develops around the axis of rotation. The fluid is thrown away from the centre, and heaped around the margin of the vessel.

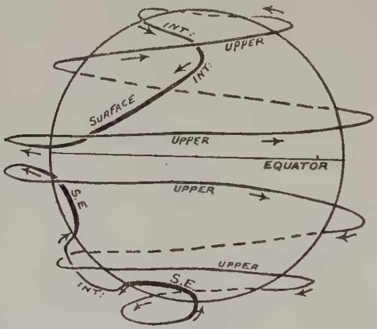

Fig. 89. Generalized diagram showing two (of many) possible paths of a body of air rising at the equator to the upper layers and then reaching the pole, and flowing back by the intermediate and surface currents. Heavy lines show lower winds.

There are somewhat parallel conditions near the poles. The air is moving towards the axis of rotation in the upper layers, and sinks down near the South Pole (see Fig. 87). The air tends to 'be piled away from the axis' to form the high-pressure belt at 35° S. ; while there arises an area of low pressure at 66° S. surrounding the pole.

Further, we have seen that at the surface there is a preponderance of winds moving to the west in the trade-wind belt north of 30° S. and moving to the east in the cooler regions south of 30° S. (see Fig. 87). Both these winds have a component urging them to the left (in the southern hemisphere). Hence the opposing thrusts of these two dominant winds tend to build up the high-pressure zone along latitude 30° S.

In the same way the westerly winds near 60° S. tend to move away from the pole (to the left), and so the air is reduced in the polar regions and heaped up towards the high-pressure zone at 30° S.[1]

One of the most difficult problems in meteorology is to explain why these two belts of pressure break up into the whirling eddies which are called cyclones and anticyclones. There are usually from five to eight eddies in each of the four belts. Some of these are almost permanent, being anchored as it were to localities favouring their formation. Most, however, drift at about twenty miles an hour to the east, in accord with the general movement of the atmosphere in temperate regions. The problem is more fully discussed in the chapter dealing with the Highs and Lows.

The Monsoon Winds

The best examples of the effect of the variation of insolation on the dominant winds is given by the monsoons. These are described by Hann as ' convection currents with a yearly period '. ' Monsoon ' is derived from an Arabic word meaning ' season', and they are the chief seasonal winds of the globe.

The land during summer becomes much hotter than the surrounding sea. Thus the interior of West Australia has an average of 90° F. in January and 60° F. in July, while the sea adjoining NW. Cape does not vary much from 70° all the year round. Greater differences occur in larger continents. As a result there is a local ' furnace effect ' in midsummer in all such lands, with a consequent special summer wind circulation.

These monsoon winds do not characterize the central equatorial regions so much as those near the two tropics. At the equator the temperature variation is slight through the year, and greater effects obtain at about latitude 10° or 20°. Even the coldest regions, however, as in Kamschatka and Greenland, have a similar monsoon effect.

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[1] This dynamical aspect of the origin of the belts is set out clearly by McEwen in the U.S.A. *Monthly Weather Review* for January 1914 (Washington).

The principles underlying these winds can be best illustrated by a diagram based on Hann (Fig. 90). Any large land mass exhibits this seasonal change (in either of the hemispheres), provided it be neither close to the equator nor to the poles. In summer in the southern hemisphere (January) onshore winds arise which are deflected somewhat to the left (by Ferrel's law), and so give rise to a local circulation (given at D). Here are north-west winds in the north, south-east winds in the south, west winds in the west, and east winds in the east. These are all well illustrated in the northern half of Australia in midsummer (Fig. 91).

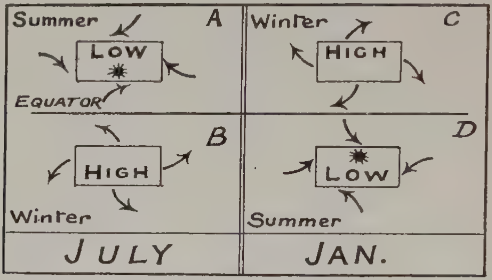

FIG. 90. Diagram illustrating monsoon changes, where the rectangle represents a large land mass. The position of the sun over the low pressure area is indicated by a black circle.

In Australia the theoretical winter effect shown at B in Fig. 90 is not so well exemplified in Fig. 91. We must turn to India to see the most striking examples of the monsoons.

THE INDIAN MONSOON. Here in the interior of the largest continent is the greatest range of temperature. In northern Siberia it amounts to 95° C. (or 171° F.); but the chief monsoon effect is in north India and Persia, where a large warm ocean is close at hand. In these lands the extreme range is about 45° C. (or 88° F.). Thus the land mass in summer is about 20° C. warmer, and in winter about 20° C. cooler, than the Indian Ocean.

As a consequence the warmer air is pushed upward by the cooler and denser air flowing in from all sides (Fig. 90). In July this leads to surface winds blowing radially towards the region indicated. Owing to Ferrel's law they are deviated to the right, so that

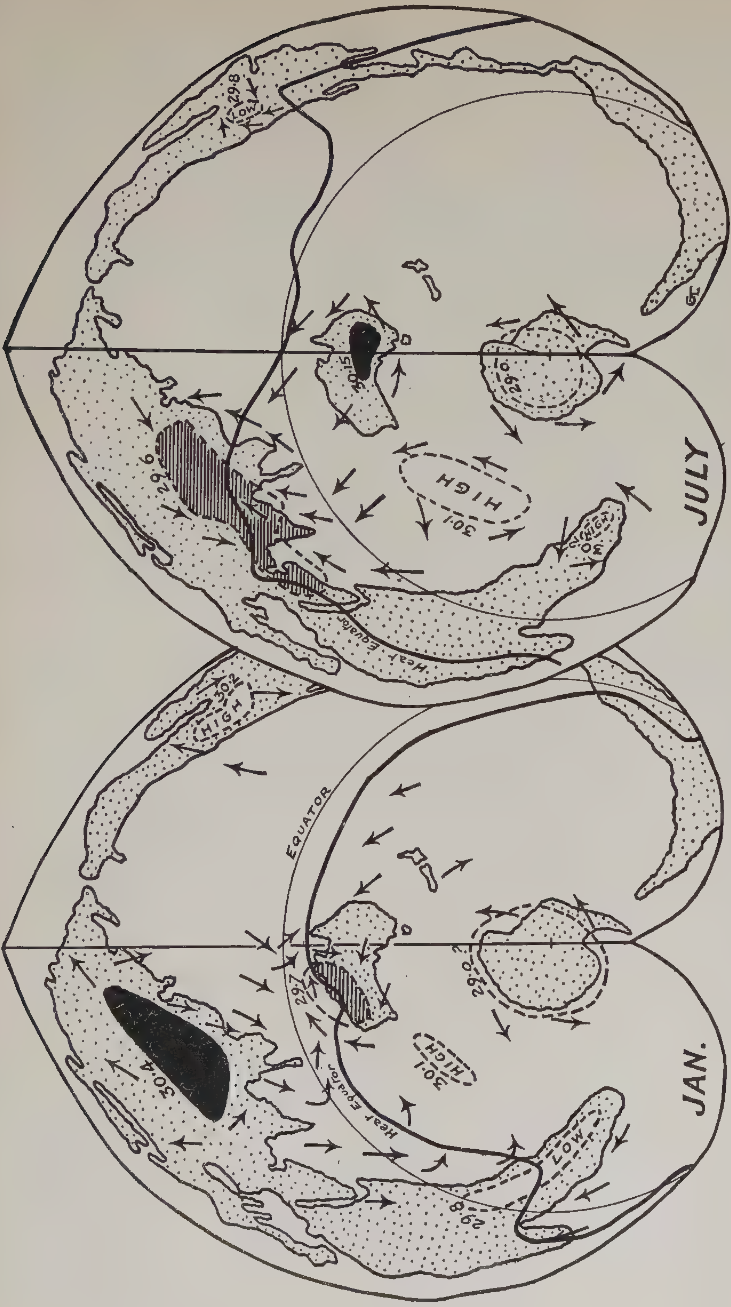

Fig. 91. The seasonal pressure changes leading to the monsoons of Asia and Australia. The change in the heat equator is also shown. High pressure is black, low pressure is ruled. (Sylvanus projection.)

the winds from the Indian Ocean blow from the south-west and not from the south, and similarly in other quarters.

This summer south-west monsoon is strongest in the hottest months, but becomes dominant about April at Colombo and continues till October. The following table shows average data, where the figures represent observations twice a day.

Wind Direction at Colombo

Direction.	*Jan.*	*Mar.*	*May.*	*July.*	*Sept.*	*Nov.*
North	**18**[1]	4	1	—	—	9
North-east	**20**	12	3	1	—	11
East	—	1	1	—	—	2
South-east	1	1	2	—	1	—
South	—	1	2	3	3	2
South-west	3	13	**38**	**32**	**37**	6
West	2	13	11	19	15	9
North-west	**18**	**16**	3	6	4	**19**
Calm	—	—	1	1	—	2

[1] This means 18 out of a possible 62 for the month.

The winter monsoon merely reinforces the normal trade wind in the south of India, and blows from the north or thereabouts from November to March.

In the China seas the north-west wind blows from November to January and the south-east wind from April to August.

In Turkestan the monsoon is SE. in winter and NW. in summer, since it lies on the *west* side of the monsoon centre.

In India the SW. monsoon stream is about four kilometres thick, while the NE. monsoon only reaches half so high.

In Java at Tosari (5,874 feet elevation) Hann states that the north-west monsoon is hardly noticeable, and the south-east trade blows all the year. The steam-banners of the Java volcanoes also show no monsoon effect over 6,600 feet.

One interesting point shown clearly by the maps (Fig. 91) is the manner in which the wind changes direction on crossing the equator. Thus in January the north-east monsoon of the Indian Ocean (a reinforced trade wind) crosses the geographical equator to reach the warmed areas under the southern sun (which lies over the heat equator near the Tropic of Capricorn). But on doing so it immediately swings to the east in accord with Ferrel's law, and reaches the northern coasts of Australia as a north-west wind.

In a similar fashion in July the air in the south-east trade moves very strongly over the southern Indian Ocean, becomes slower as it approaches the equator, and gradually changes direction so as to blow from the south-west; and increases in strength as it develops into the south-west monsoon storms of the Arabian Gulf.

The shifts in the wind belts can be represented diagrammatically by means of the two vertical sections given in Fig. 92. Here the three land masses of most interest to Australian students (Antarctica, Australia, and Asia) are shown in relation to the dominant surface winds, and to the position of the sun at the solstices in January and July. (See also Fig. 90.)

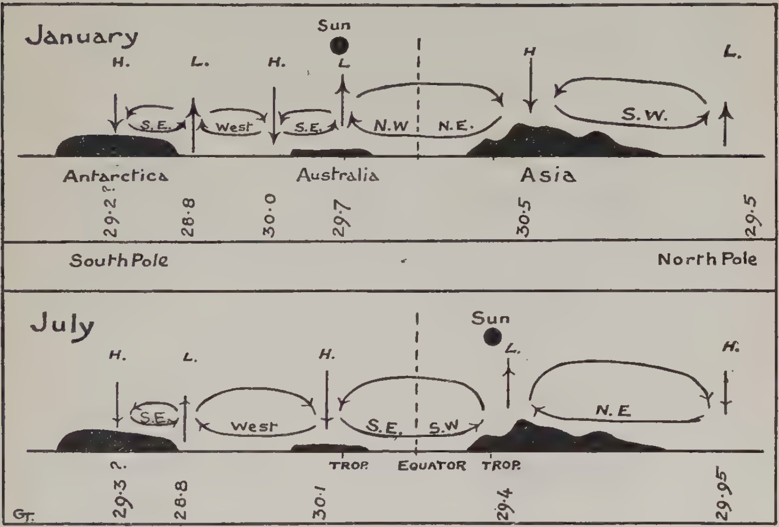

FIG. 92. Diagrammatic vertical sections to show the shifting of the monsoons and wind belts with the sun. The actual pressures shown by the figures below.

The circulation near the surface can be looked upon as broken into a series of semi-independent whirls. Each whirl lies between a High and a Low, and the position of these will be found to agree with the centres plotted in Fig. 91. The lower portions of the whirls are labelled to correspond with the surface winds, the upper portions probably merge into the upper air drift and do not keep their identity to anything like the extent suggested by the figure. Note especially the changes over Asia and northern Australia.

At the poles the land never rises to the temperature of the sea, and so there cannot be that reversal of winds which constitutes the monsoon. Around the South Pole the open ocean is always near 30° F. In summer the Ice Plateau is much colder than the ocean at 66° S., probably 30 or 40 degrees colder. In winter the difference is still more marked. The open ocean (now in latitude 60°) is about +30°, and the plateau probably as low as −50° F., a difference of 80 degrees.

It is worth noting that Buchan's maps of the North Pole show no special polar anticyclone except perhaps in May. We may, therefore, deduce that the South Pole, if there were no elevated icy plateau, would show no intense area of high pressure. The paradox of an apparently *enlarged* high pressure area in summer (see January in Fig. 91) is probably entirely due to the abnormal topographic conditions.

LAND AND SEA BREEZES

Just as the annual revolution of the earth round the sun is accountable for the seasonal monsoons, so its daily rotation (leading usually to cool nights and warm days) is responsible for a daily monsoon which is familiar to us as the alternation of land and sea breezes (see Fig. 93).

As Ward[1] points out, the early Australian explorer, William Dampier, in 1705 described the phenomenon in terms which will well bear quotation to-day.

> 'These sea breezes do commonly rise in the mornings about nine o'clock; they first approach the shore, so gently, as if they were afraid to come near it, and ofttimes they make a halt and seem ready to retire. . . . They come in a fine small black curl upon the water, when all the sea between it and the shore is as even as glass. It increaseth gradually till twelve oclock, and lasts till two or three a very brisk gale. About five o'clock it is lulled asleep and comes no more till next morning.
>
> 'Landbreezes do blow in the night and rest in the day. In the evenings they rouse out of their private recesses and gently fan the air till next morning. . . . The sea breezes are very comfortable and refreshing.'

The origin of these breezes is of course the differential warming of land and sea. The sun has approximately twice the effect on the land owing to the high specific heat of water. Blandford showed that the air over the land, heated by contact with the warm ground, is expanded much more than that over the sea, where the heat is largely used in evaporating the water.

The result is that the isobaric surfaces are expanded over the land, and given a slope seawards, the steeper slope being aloft. Down this slope the upper strata of air over the land slide seaward, and thus an increment of pressure is produced at some distance offshore. This produces a flow inshore.

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[1] Ward, in U.S.A. *Monthly Weather Review* for May 1914.

Seeman has shown that at Rio Janeiro the sea breeze is kept away from shore because the expanding air over the land pushes *outward* as well as upward. This outward push diminishes as the rate of increase in temperature over the land diminishes.

Sandström points out that there is no downrush of air over the sea as some diagrams suggest. The air probably flows away horizontally over the cooler surface air of the sea. A more complete vertical circulation may occur during the night, when the air rises over the warmer water and is continuously sinking over the rapidly radiating land surface.

These breezes occur chiefly in clear weather when the pressure gradients are low. Thus anticyclonic conditions are much more favourable than cyclonic. Also in the equatorial coastal regions—being free from strong gradients—they are very abundant.

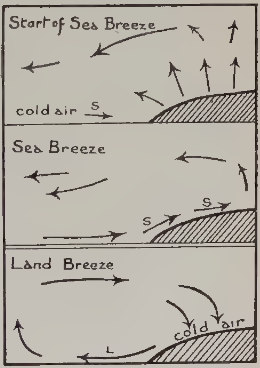


FIG. 93. Land and sea breezes. The sea breeze starts some distance away from land. The upper offshore wind does not sink to the sea. The land breeze probably shows a more complete circulation.

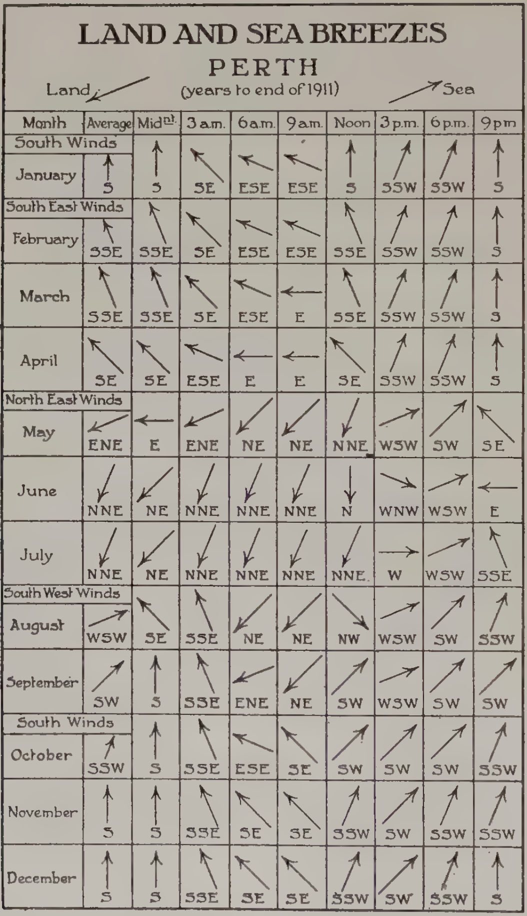
They have a very local extent. They penetrate usually only 20 miles inland, though at Calcutta they are 68 miles from the sea. In New England, U.S.A., they move inland with a velocity of 10 or 15 miles per hour.

The sea breeze at New York only extends up about 400 feet. Measurements at Melbourne with the self-recording theodolite show that sounding balloons usually rise through the surface layer of wind in about 90 seconds, which gives a thickness of much the same order.

Since so large a portion of the population of Australia lives on the seaboard, these winds are of great importance. Their general characteristics are much the same, and the data for Perth are given in Fig. 94. Here the land lies to the east of the sea. The dominant regional winds at Perth are somewhat as follows :

Summer . . .	October–January	South wind.
Autumn . . .	February–April	South-east wind.
Winter . . .	May–July	North-east wind.
Spring . . .	August–September	South-west.

At Perth the invigorating sea breeze—called the 'Doctor'—blows from WSW. during the afternoon; while a land wind (ENE.) sets in when the land has cooled below sea temperature in the early morning. The sea breeze is most active when the land is *much* warmer than the sea, i.e. in summer. The land breeze is most active for similar reasons in winter.



Month	Average	Midnt.	3 a.m.	6 a.m.	9 a.m.	Noon	3 p.m.	6 p.m.	9 p.m.
South Winds									
January	S	S	SE	ESE	ESE	S	SSW	SSW	S
South East Winds									
February	SSE	SSE	SE	ESE	ESE	SSE	SSW	SSW	S
March	SSE	SSE	SE	ESE	E	SSE	SSW	SSW	S
April	SE	SE	ESE	E	E	SE	SSW	SSW	S
North East Winds									
May	ENE	E	ENE	NE	NE	NNE	WSW	SW	SE
June	NNE	NE	NNE	NNE	NNE	N	WNW	WSW	E
July	NNE	NE	NNE	NNE	NNE	NNE	W	WSW	SSE
South West Winds									
August	WSW	SE	SSE	NE	NE	NW	WSW	SW	SSW
September	SW	S	SSE	ENE	NE	SW	WSW	SW	SW
South Winds									
October	SSW	S	SSE	ESE	SE	SW	SW	SW	SSW
November	S	S	SSE	SE	SE	SSW	SW	SSW	SSW
December	S	S	SSE	SE	SE	SSW	SW	SSW	S

FIG. 94. Land and sea breezes. Perth.

In winter the normal north-east wind and the land breeze are assisting each other during the morning. In the afternoon the sea breeze is noticeable practically throughout the year.

CHAPTER XII

WATER VAPOUR IN THE AIR

Molecular Considerations. If a pan of water be freely exposed to the air, we know that sooner or later the water will disappear—it will evaporate. (This has been discussed to some extent in an earlier chapter.) It is a matter of common knowledge that the warmer the air the quicker the evaporation. Also a windy day increases the rate of evaporation.

The molecules of water vapour can be thought of as darting in and out of the liquid surface. If the air is ‘ saturated ’, as many molecules will return as leave the water ; and the result is that evaporation ceases. If on the other hand the air is dry and the ‘ vapour pressure ’ (of the water already in the air) is low, the exchange of molecules will be greatly to the loss of the liquid water.

Each of the molecules of water building up the liquid is to be thought of as possessing some movement, which, however, differs with various molecules. Speaking generally, the more rapid the vibration of the molecule (i. e. the greater its kinetic energy), the more likely is it to fly away from the liquid surface. Hence on the whole the kinetic energy of the liquid soon diminishes through evaporation (the most lively molecules being lost first). It is this change in kinetic energy which is manifested in change of temperature. We therefore see that evaporation is usually accompanied by a cooling of the liquid.

The devices which make use of this principle for cooling food, &c., all aim at increasing the surface from which the livelier molecules may be set free. Thus we use porous jars or muslin covers, &c., which expose a large damp surface to the free air. They are placed in a draught if possible so that the wind may assist by mechanically carrying off the evaporated water. As we shall see, this is the basis of the wet-bulb thermometer.

There is another aspect of the molecules which we must study, which is concerned with what happens when water changes to steam, or ice changes to water. This ‘ change of state ’ involves very great changes in molecular energy. We can picture the water molecules as cramped together with very restricted vibrations when they are in the form of ice. When they are in the form of liquid water the molecules are exactly the same, but they are farther apart and their vibrations are more rapid and extend over a wider range. In a state of steam or vapour the molecules are still more free and have wider vibrations again.

Latent Heat. Let us now take two basins—one full of crushed ice, just on the point of melting; the other full of ice-cold water. If we insert a thermometer into each, the mercury will stand at 0° C. (or 32° F.). If we heat the two basins there is a remarkable difference. The water gradually increases in temperature until it is raised to boiling-point. But the basin of ice does not change in temperature until all the ice has melted.

The heat has all been used up in 'breaking apart' the molecules from their intimate relation in the solid, and changing the state to that of a liquid. The heat has in fact been changed into molecular work, and is not used to augment the kinetic energy of the water molecules.

The unit of heat is the amount of heat necessary to raise the temperature of a gram of water through 1° C. The amount of heat necessary to break apart the molecules of a gram of ice and convert it into a gram of water (at the *same* temperature 0° C.) is 79 such units. The heat thus 'hidden' from the thermometer is called the latent heat.

To change from a gram of water at 100° C. to a gram of steam at the same temperature uses up no less than 536 units.

The converse operation is of almost greater importance in meteorology. If water vapour is condensed to the liquid state—such as when moist air is elevated and cooled—then this latent heat is set free. This supply of energy accounts largely for the violence of tornadoes.

Evaporation. In a dry country like Australia it is important to know the amount of evaporation which is taking place. It is usually measured by means of iron tanks (3 feet in diameter), which are sunk in the ground and protected from animals. The lowering of the water-level is recorded by a gauge affixed to the side.

A score of such stations are scattered over Australia, and from them it is possible to draw a map showing the regions of large and small evaporation. The isopleths through places of equal evaporation are naturally much the same as the wet-bulb isotherms (see p. 121). They are concentric with the coast, and the highest evaporation is in the hot interior in the north of West Australia.

The whole of central Australia has an evaporation of some 9 feet per year, while the rainfall is less than 9 inches. This is the clue to the comparative lack of vegetation.

Only along the east and south coasts are there any districts where the rainfall balances the evaporation. The favoured regions are shown in black on the map. Here grow the tropical jungles of the north and the giant eucalyptus of the south. Here in Tasmania is the 'Horizontal Scrub'—which is a true temperate jungle, so closely massed that one can walk over the top of 30 feet of vegetation.

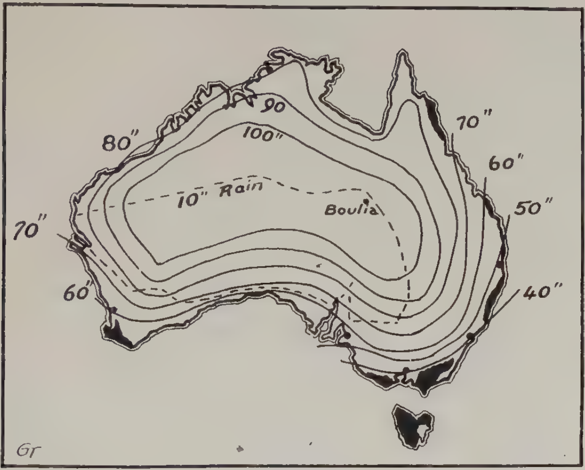


FIG. 95. The relation of evaporation to rainfall. Isopleths show inches of evaporation. The regions where rainfall balances evaporation are black. (Partly from Hunt.)

EVAPORATION IN AUSTRALIA (IN INCHES). (AFTER HUNT)

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*
Melbourne (Victoria) .	6·3	5·0	3·9	2·3	1·5	1·1
Boulia (SW. Queensland) .	15·7	12·2	10·7	9·4	6·9	5·8

	July.	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Total.*
Melbourne (Victoria) .	1·1	1·5	2·2	3·3	4·5	5·7	38·4
Boulia (SW. Queensland) .	5·4	6·7	9·3	11·7	15·0	15·6	124·5

HUMIDITY. When a volume of air contains all the water vapour it can hold (without deposition as mist or rain) it is said to be *saturated* for that temperature. By merely raising the temperature we increase the amount of water vapour which can be contained. By merely reducing the temperature we compel some of the water to become visible as mist, the air in this case of course still remaining saturated.

As the temperature rises above freezing-point the amount of water which can be retained in the air rapidly increases. This is shown in Fig. 96, where the conditions of the saturation of one cubic metre of air are charted. From −30° C. to 0° C. its capacity slowly increases from near zero to 5 grams. Thereafter its capacity rapidly increases to 35 grams as shown. At normal temperatures (i.e. around 60° F.) a cubic metre (about 35 cubic feet) of saturated air contains 13 grams of moisture.

Water vapour weighs much less than dry air, the ratio being as 5 to 8. Hence dry air is heavier than moist air (at the same temperature and pressure). At 20° C. a cubic metre of dry air weighs 1,205 grams, whereas the same volume of saturated air (at the same pressure) weighs only 1,194 grams. (Hann.)

RELATIVE HUMIDITY AND DEW-POINT. Normally the air is not saturated; it contains only a percentage of the amount it could retain if the maximum were available. This percentage is called the *Relative humidity*. Thus if air is saturated, its relative humidity is 100.

In temperate regions this only occurs in the midst of a thick mist or while rain is falling heavily—and never endures for long. On the tropical coasts, however, the percentages are very high throughout the year. Thus Batavia has an average relative humidity throughout the year of 83 per cent.; and the Cameroons (Africa) of 88 per cent.

It will be understood that the temperature at which saturation occurs varies with the amount of moisture in the air. If the air contains much moisture (say, over 15 grams to the cubic metre) the saturation temperature (or dew-point) will be above 64°. If it is very dry the temperature must be greatly lowered before the saturation-point is reached.

Suppose it is a warm muggy day with a temperature of 86° F., and a cubic metre of air contains, say, 25 grams. Let us investigate its humidity with the aid of Fig. 96.

At 86° F. 1 cubic metre of saturated air contains 32 grams.

At 78° F. (see Fig. 96) 1 c.m. of saturated air contains 25 grams. Hence the dew-point on this particular occasion is 78° F. The air only contains 25 grams, whereas it *could* contain 32 grams. Hence the *relative* humidity is 25 × 100/32, or 78 per cent. The actual amount of water present (per unit volume) is called the *Absolute humidity*. In this case it is obviously 25 grams. Shortly: at any given temperature

$$\text{the Relative Humidity} = \frac{\text{Absolute humidity}}{\text{Saturation value}}.$$

Let us now work out an example for a clear cool day in winter. Suppose the temperature is 50° F. and a cubic metre of air contains 5 grams of water vapour. This is the *absolute* humidity at the time. The air *could* contain 10 grams (see Fig. 96) if it were saturated. Hence the relative humidity is only 50 per cent.

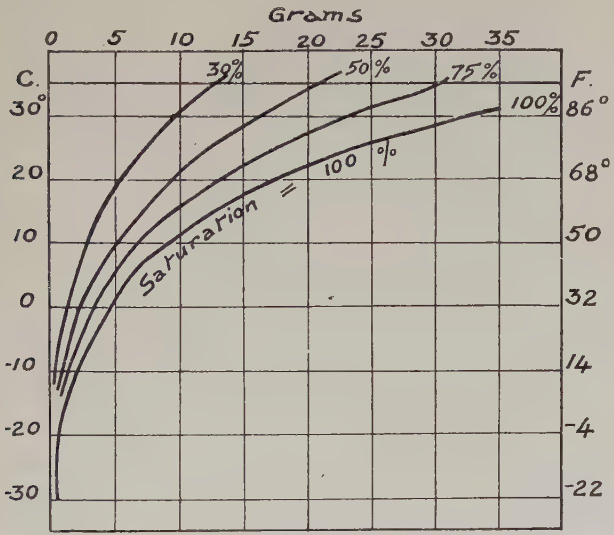


FIG. 96. Weight of water vapour in one cubic metre of saturated air (100 per cent.). Also weights for various other relative humidities; 75 per cent., 50 per cent., and 30 per cent. of complete saturation.

It is a lengthy and somewhat complicated operation to estimate the amount of water vapour in a cubic metre of air. It is usually done by allowing certain chemicals to absorb the moisture and by determining their increase in weight.

But there are many indirect ways of estimating the dew-point and the humidity, two of which we may now consider. The instrument used is called a hygrometer.

THE TIN-CUP HYGROMETER. Let us take a bright tin pannikin—which is a very good conductor of heat—and fill it with water at the ordinary temperature of the room (say 50° F.). In this insert a thermometer, preferably one without a wooden case.

Now let us cool the water by adding ice-cold water or by some similar means. The water is chilled and so is the tin cup, and the latter cools the air immediately around it to approximately the same temperature. As the temperature of the tin falls to 40° F. we see a film of dew form on the outside of the cup, and our experiment is complete.

This tells us that at 40° F. the layer of air surrounding the tin cup is unable to hold up all its water vapour, and some is deposited on the cool tin. The air just here is in fact saturated. Hence for the temperature and moisture of the room at that time 40° F. is the *dew-point.* We can also say from the tables (or from Fig. 96) that 1 cubic metre of the air contains just about $6\frac{1}{2}$ grams of water vapour, and the relative humidity is about 75 per cent.

It is important to note that any change in the temperature, or in the water vapour in the room, immediately alters the dew-point and the humidity.

THE WET-BULB THERMOMETER. The apparatus which is usually used to obtain the humidity is a modification of the ordinary thermometer. We have learnt that evaporation tends to cool the surface from which evaporation takes place. If the air above the evaporating object (which in this case is wet cotton or linen) is already nearly saturated, the cooling effect is very slight. If the air is dry and far from saturation, the cooling effect is very considerable.

Two thermometers are placed side by side. One is the ordinary dry-bulb thermometer. The other has the bulb enclosed loosely in a linen bag to which are attached many strands of cotton wick. The strands hang down into a glass containing water, so that the water keeps the cover always moist (Fig. 97).

On a bright clear day we shall find the wet bulb is cooled considerably below the dry bulb. For instance the wet bulb may show 70° F., and the dry bulb 80° F. From special tables which we may consult—or from the condensed graph in Fig. 98—we see that the relative humidity is 60 per cent. Similarly wet bulb 90° and dry bulb 95° will be found to give a relative humidity of 80 per cent.

In Fig. 97 the wet bulb is reading 64°. The dry bulb alongside (at *r*) is shown at 66°—which means that the air is muggy, evaporation is slight, and the relative humidity is 89 per cent. A second example with the wet bulb at 64° and the dry bulb at 72° (at *s*) means that evaporation is rapid and that the relative humidity is 62 per cent.

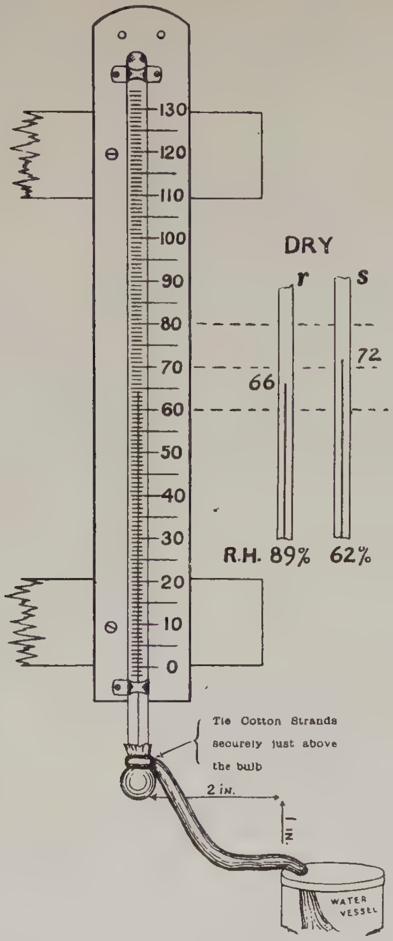


FIG. 97. The wet- and dry-bulb hygrometer. The wet bulb stands at 64° F. If the dry bulb (as at *r*) reads 66° F. at the same time, the relative humidity is very high (89 per cent.). If it reads 72° F. (as at *s*), then the relative humidity is only 62 per cent.

Somewhat complicated tables must be referred to in order to obtain the relative humidity from the two readings of the thermometers. But these tables are given in graphical form in Fig. 98, where the desired humidity can be obtained fairly accurately by inspection. For instance, the examples labelled *r* and *s* in Fig. 97 are worked out on Fig. 98.

Relative Humidity in Australia. If we plot the relative humidity data for Australia on series of monthly maps, we see that the lines of equal humidity are concentric and more or less parallel to the coastline (Figs. 99–102).

The extreme months appear to be June (or July) and October, which is a somewhat unusual departure. One would expect the extremes to be six months apart.

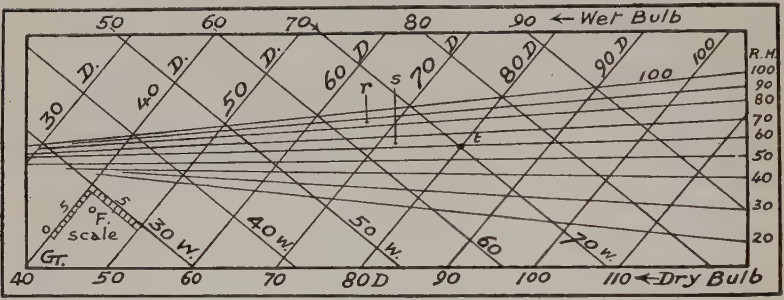
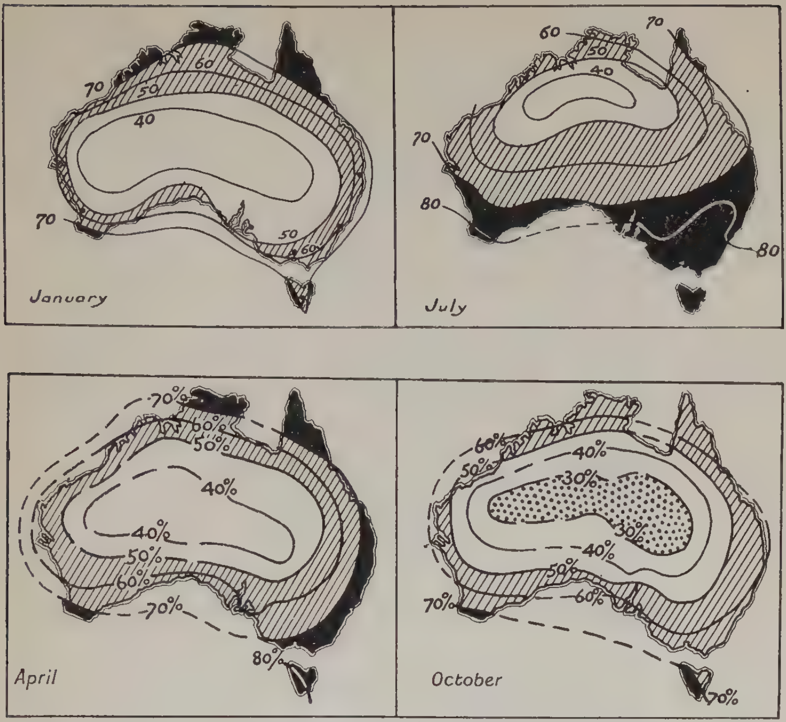


Fig. 98. Determination of relative humidity from the wet- and dry-bulb thermometers. Follow the dry-bulb reading (say 80 D) until it meets the synchronous wet-bulb reading (say, 70 W) at *t*. This lies close to R.H. line 60. The inset scales may be used for intermediate degrees of temperature. *r* and *s* illustrate the conditions in Fig. 97.

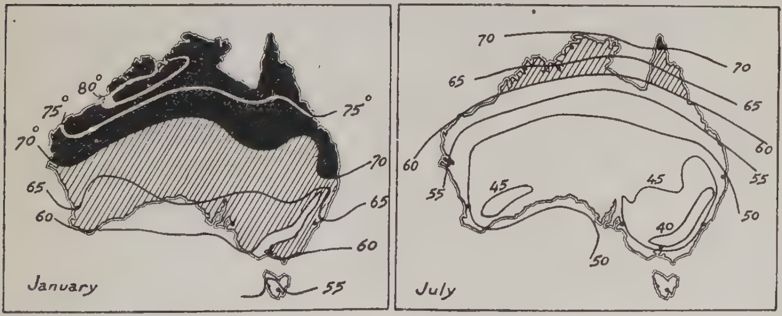
The 'centre of lowest humidity' moves north and south with the sun, being near Powell's Creek (N.T.) in July (Fig. 100) and near Oodnadatta (S.A.) in January (Fig. 99). The most humid station on record is Kiandra, an upland town near Kosciusko, and 4,640 feet above sea level. Here during the eight months March–September the humidity is over 77 per cent. The effect of the mountain region is shown by the bulge in the 80 per cent. isopleth in the July chart.

Further details as to the distribution of humidity will be found in the chapters dealing with climatology.

Wet-Bulb Isotherms. The wet-bulb thermometer is the most useful instrument in common use for determining the degree of comfort at any particular locality. Its records are of paramount importance in a discussion of the suitability of the tropics for



FIGS. 99–102. Average monthly humidity charts for Australia. High humidities (over 70 per cent.) shown black.



FIGS. 103, 104. Average wet-bulb charts (after H. A. Hunt). Regions shown black have a ‘muggy’ climate.

white settlement. This is a climatological problem and will therefore be discussed later, but the two extreme monthly charts for the year deserve some consideration at this point (Figs. 103 and 104).

The wet-bulb isotherms are of course not very different from the ordinary isotherms. But when the rainy season is affecting a region, then evaporation is slow and the wet bulb reads nearly the same as the dry bulb. In the tropics, when the 'mugginess' is marked and discomfort is considerable the wet-bulb readings will be at their maximum.

Accordingly in midsummer the whole of our tropical region shows high wet bulbs, for it is hot and rainy at the same time. This uncomfortable region is shown in black in Fig. 103. In midwinter (July) the north (as we shall see later) is absolutely arid. Though the dry-bulb readings are high, yet evaporation is so active that the wet bulbs remain low. Only the merest fringe—at Darwin and Cape York—have readings above 70° F. (see Fig. 104).

In the south the rain is almost continuous on the coast. The humidity is high, but the temperatures are naturally low, and so the wet bulb is low—though it differs very little from the dry-bulb reading.

DEW. The experiment already considered, where the dew-point was determined by the film of water on a tin cup, gives the key to the origin of dew. There we cooled the layer of air surrounding the cup much below the temperature of the main body of air, and dew was deposited on the cup.

In nature the natural radiation at night cools the ground often many degrees below the temperature of the air above. Such objects as blades of grass expose a large surface and are very rapidly chilled, hence they are the first usually to exhibit a deposit of dew.

Glaisher showed that the lower layers of air exposed to free radiation were much colder than the standard thermometer placed in a screen near by.

Height above turf (inches)	144	96	48	6	3	2	1
Lowering of temperature (F.)	0	0·18	0·54	2·3	3·98	4·86	5·58

Hence just where the blades of grass project into the air the temperature may easily be 6 degrees below the standard air temperature. A reference to the table in Fig. 96 will show that if the screen temperature is 68° F. and the air contains

16 grams of water vapour in a cubic metre—then a decrease of 6° F. will bring the turf below the dew-point. The air here will be over-saturated, and some grams of water will be deposited on the nearest cold objects—the blades of grass.

In some localities the difference between the screen temperature and the temperature of the grass (as taken by a 'terrestrial minimum' thermometer) is very great.

Records on the Tambourine Plateau (1,900 feet high and 38 miles south of Brisbane) sometimes give such extreme differences as 26·8° between the screen minimum and the adjoining terrestrial thermometer (e.g. 29 July, 1917).

AVERAGE DIFFERENCES BETWEEN SCREEN AND TERRESTRIAL READINGS

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Sydney, N.S.W.	4·8	4·8	5·2	5·7	6·1	6·0	6·2	6·6	6·7	6·3	5·6	5·1
Tambourine, Q.	6·8	6·9	8·3	11·1	15·1	14·2	15·2	12·1	11·4	9·7	8·6	8·0

FROST. This term is somewhat loosely used to denote either hoar-frost (frozen dew), or temperature below 32° F. generally.

Hoar-frost has the same origin as dew and merely indicates that the tips of the grass and other cooled objects have fallen below 32° F. There is usually in Australia no formation of ice on pools under such conditions, and the official temperature record (in the screen) by no means falls to 32° F. in most cases.

Thus at Melbourne the following figures were obtained as 'means of extremes'.

EXTREME MINIMUM TEMPERATURES

	Screen.	*Terrestrial (on ground).*
June	33·6° F.	27·7° F.
July	31·8° F.	25·5° F.
August . . .	33·5° F.	27·4° F.

Hence the screen temperature is usually 6° higher than that of the ground when radiation is excessive.

Almost the whole of Australia is liable to frost in the winter months; but it is not of such economic importance as in most white countries, for frost is common only in the south-east corner.

The north, north-west, and north-east littorals have had only one or two records of frost in a dozen years. Thus Palmerville, in Queensland (Fig. 105), experienced frost on 30 June, 1901. Kamerunga (near Cairns) was visited by frost on 30 July, 1909, and Anna Plains (in W.A.) on 18 June, 1907.

The lowest temperature at Darwin for many years was 55·8° F. on 30 July, 1884.

One of the coldest spells experienced at Melbourne occurred in May 1916. The following shows the screen and terrestrial temperatures, and two typical charts are given in Figs. 106 and 107.

Frost at Melbourne, May 1916

Date	25	26	27	28	29	30
Screen (min.) . .	33·2	32·3	33·8	31·9	29·9	35·3
Terrestial . . .	22·2	21·1	24·0	24·5	22·3	28·5

For almost a week a High covered south-east Australia. This implied calm clear nights, very favourable for strong radiation, and accordingly the terrestrial (soil) thermometer was well below freezing-point every night. Two charts for the 26th and 29th of May are given in Figs. 106 and 107. Here also are plotted the minimum (screen) temperatures. The isotherms for 50°, 40°, and 30° are concentric about the Victorian Highlands. The effect of the sea in warming the east of New South Wales is very noticeable.

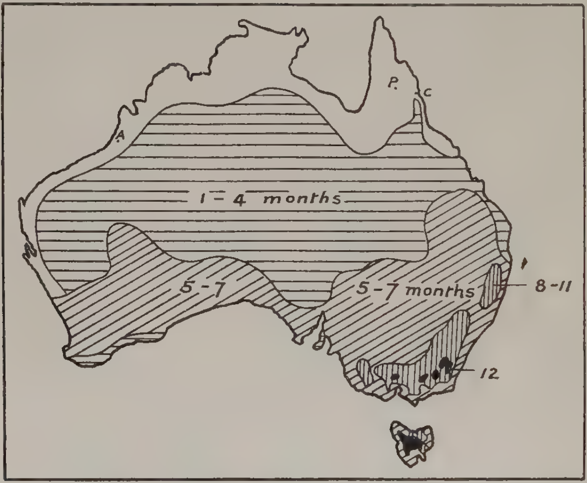
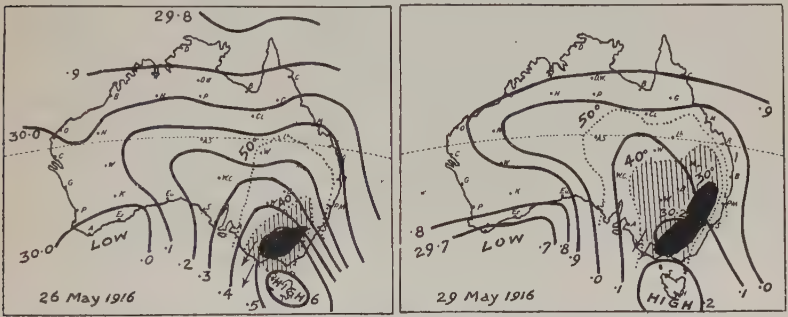


Fig. 105. Frost map for Australia (after H. A. Hunt). Showing number of months per year when frequent frosts may occur (Anna Plains, Palmerville, and Cairns indicated).

Fog. Of perhaps greater importance in our warm countries is the phenomena of Fog. This is one of the greatest dangers to traffic, whether on land or sea, and therefore merits special attention from the meteorologist. The conditions for fog are much the same as those for dew and frost. They are favoured by radiation and so occur chiefly in winter, especially when Highs are in control of the weather.

Fogs[1] may provide no inconsiderable portion of the moisture supply in the country, especially among the hills. Fogs are very local phenomena, the general causes in the way of pressure, &c., which favour their development in one locality not being at all effective in others near by. One factor must of course be present in every case, that is the presence of water vapour in the lower stratum of air in sufficient quantity to produce saturation, before the cooling by radiation or otherwise has reached its limit.



FIGS. 106 and 107. Charts illustrating frost at Melbourne. The dotted lines are minimum isotherms for the early morning, but below 30° F. is in black. Notice the cold *North* wind of winter.

The air is usually dry in an anticyclone, when radiation is strongest, and frosts alone occur. But when a High follows soon after a Low, so that a clear calm night follows rain, then fogs are almost certain to be formed.

On 26 July, 1910, conditions were very favourable for fog in Melbourne. A low-pressure area had just moved to the east, and drizzling rain had fallen all day over southern Victoria (shown dotted in Fig. 108). The air near the surface was therefore moist. A well-developed High advanced from the west. Near its centre a cloudless sky favoured great radiation and a rapid fall of temperature. On the evening of the 26th (from 8.30 to 11.30) occurred one of the heaviest fogs on record. The thermometer at 9 p.m. was 42·7°—a drop of 7° F. from the same time on the

[1] See the description of fog in Melbourne given by Quayle in *Climate and Weather*, p. 85.

25th. The minimum for the night (26–7) was 35·6°, or a drop of 4·4° degrees from the preceding night. As the chart shows the wind was light, and as the centre of the High was to the south it was from the south-east. Hence it was vapour-laden from the Bass Straits.

Fog Prediction. Thus high humidity and low temperature are the chief factors determining fog. Major Taylor of the Aviation Corps in England has elaborated a method of forecasting fog from the readings of the dry- and wet-bulb thermometers. I have illustrated the principle in Fig. 109, as applied to Melbourne.

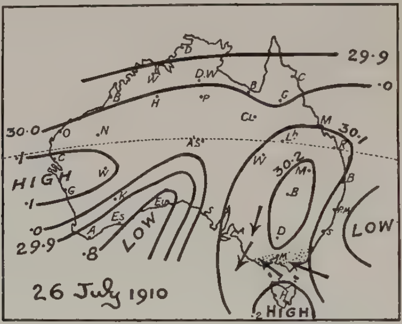


Fig. 108. Weather chart (9 a.m.) preceding an unusually heavy fog in Melbourne.

The ordinates for Fig. 109 are dry-bulb readings at 9 p.m., and differences between wet- and dry-bulb readings at the same hour. Suppose the dry bulb is reading 45·4° at 9 p.m. and the wet bulb 44·0°. Then the difference is 1·4° and the *plot* for this observation is shown at A (in Fig. 109). Since this point lies within the black triangle X Y Z, the chances are greatly in favour of fog ensuing in the night. I have plotted many cases of low temperature and high humidity (both of which conditions are necessary to bring the points plotted within the triangle), and in 70 per cent. of the cases fog has resulted.

This is obviously an empirical method, but is based on the two factors which always determine fog. (In Fig. 109 the dots show where fog has followed, the crosses where fog has not followed when the necessary conditions were fulfilled.) The average temperatures at 9 p.m. for the three coldest months are shown in the lower right-hand corner of Fig. 109.

The triangle X Y Z (in Fig. 109) expresses temperature conditions wholly below the average for the coldest month, and it also

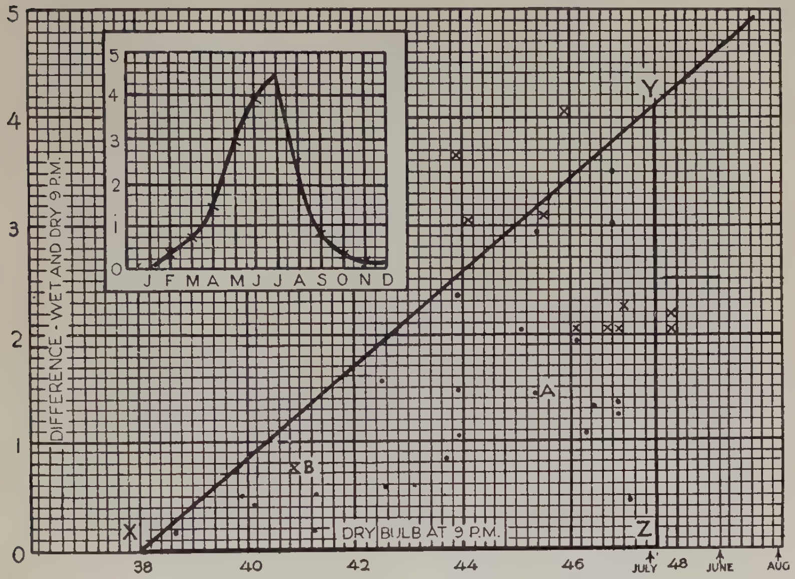


Fig. 109. Fog prediction (by the method of G. I. Taylor) at Melbourne. If the plotted data lie within the triangle X Y Z, then in 70 per cent. of the cases fog will ensue. (Inset is the average number of occurrences of fog through the year at Melbourne.)

expresses high humidity, for in most of the plotted points the difference between the wet- and dry-bulb readings is only 3°.

Fogs are naturally more prevalent in winter. The order of abundance is July, June, and May; and these months usually include two-thirds of the year's total. (See the inset in Fig. 109.)

CHAPTER XIII

CLOUDS AND THEIR ORIGIN

There is little difference in principle between the formation of dew, fog, or clouds. All depend on the relations of saturated air and temperature ; the distinctions being in the places of origin and in the method of cooling. It is usually the cooling due to the earth's radiation which causes dew and fog, and they form near the surface. It is cooling due to ascent and expansion which operates on moist air to bring about the formation of clouds, which usually form from 2,000 to 30,000 feet above the surface.

Classification. There are many varieties of clouds, but the following table shows the more important classified according to their general elevation (see Fig. 30).

Layer.	*Approx. Height in feet.*	*Name.*	*Description.*
Upper	30,000	Cirrus	White wisps—no shadows.
	25,000	Cirro-stratus	Continuous sheet of cirrus wisps.
	20,000	Cirro-cumulus	Granulated ripples. Mackerel sky.
Intermediate	15,000	Alto-stratus	Thick grey veil.
	10,000	Alto-cumulus	Hard patchwork cloud (like ice-floes in a dark sea).
Lower	10,000 to 5,000	Cumulus	Wool-pack cloud. Flat base. Due to convection.
	5,000	Strato-cumulus	Hard dull layer with uneven lower surface.
	2,000	Stratus	High fog.
Variable	20,000 to 3,000	Nimbus	Dark 'angry' rain cloud. Anvil cloud.

Clouds may also be classified according to their shape (as in the *British Observers' Handbook*), in which case there are three main divisions.

(1)
Stratified in Continuous Layer.

Cirro-stratus = thin veil or tangled web.
Alto-stratus = thick layer, grey or blue.
Nimbus = shapeless rain cloud.
Stratus = low uniform layer.

(2)
Stratified in Ordered Cloudlets.

Cirrus = feathery clouds.
Cirro-cumulus = small flocks.
Alto-cumulus = large detached masses, some shadow.
Strato-cumulus = rolls or waves.

(3)
Cloud Heaps.

Cu-nimbus or anvil cloud 26,000 feet to 5,000 feet.
Cumulus = woolpack cloud.
Fracto-cumulus (torn by wind) = scud.

Cloud Characters. The chief difficulty in naming clouds arises because many of these types grade into each other.[1] Moreover, some authorities divide each type into many sub-types. For instance, Clayden gives nine different kinds of cirrus.

Cirro-stratus is almost always derived from cirrus and may merge into cirro-cumulus. It lies lower than cirrus in the atmosphere (as Clayden states) because vapour becomes too rare for a stratum where cirrus develops.

Cirro-cumulus in Victoria is a cloud of unsettled weather and usually travels rapidly.

These upper clouds are probably formed of ice-crystals; but the lower clouds are formed of drops of water which may remain liquid though cooled much below the freezing-point.

Alto-stratus is much thicker than cirro-stratus. Unlike the latter it never produces a halo around the sun (for a halo is due to ice crystals), though it may give coloured coronae. It is only about half the height of cirro-stratus. It is usually connected with the following type.

Alto-cumulus. Between the detached masses of this type one can often see the dark-blue sky beyond. These masses may be arranged in lines or quite irregularly. Two or three layers of this cloud may be seen in rainy weather in Victoria.

Strato-cumulus sometimes appears as great rolls arranged in parallel lines and pressed close to one another. In their centres these rolls are of a dark colour. It may often be recognized by the unevenness of its under-surface, which shows that it is not a true convectional cloud. The upper surface is billowy rather than truly cumuliform according to Quayle's observations. It is essentially a dry-weather cloud inland in Victoria, though near the sea coast it may change into a low nimbus from which misty rain falls.

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[1] Refer to Clayden, *Cloud Studies*, London, 1905, and Quayle, 'Cloud Types at Melbourne', *Meteorological Bulletin* 12, both of which I have consulted freely.

Cumulus is merely the visible head of a rising column of moist air. It shows (by its even base) the level at which the moist air reaches its saturation temperature (dew-point).

The writer personally explored a cumulus per aeroplane on 13 March, 1917. The base was at 6,200 feet above sea level. Assuming a fall of 6° C. per kilometre (3,280 feet), this would give a decrease in temperature of 11·5° C. Since the ground temperature was about 24° C., the temperature of the base of the cumulus would be about 12·5° C. By reference to tables we find that a cubic metre of saturated air at this temperature contains about 11 grams of water; and this probably represents the amount of water near the top of the column of air, which formed the cumulus cloud.

Quayle states that it is very common in front of shallow depressions with slight gradients. It develops best during the warmth of the day and tends to disappear towards evening. It is a favourable rain sign if it persists after sunset.

Cumulo-nimbus is the towering ‘ anvil ’ cloud of the thunderstorm. It often has as large a bulk as Mount Everest—reaching as high and covering as large a base (see Fig. 30).

Nimbus. ‘ This is a ready way of indicating cloud from which rain is falling, and which may be almost any cloud whatever. It will be noticed, however, especially on the south side of the Divide in Victoria, that the rain falling in front of a barometric depression comes from cloud strata of very different type from, and of much greater elevation than, the shower clouds in rear of the depression. The former are more stratiform and extensive, being due apparently to continuous ascent on inclined planes; the latter are either detached and of cumulus type, or when stratiform owe their rain-producing power to coastal uplift or small successive disturbances.’[1]

Scud is incipient cumulus at the very low level possible in front of a decided storm trough. It moves with great rapidity and cannot attain true cumulus form. It should not be called *fracto-stratus*.[1]

MEASUREMENT OF CLOUD HEIGHT

A simple way of determining cloud height, which illustrates the official method and is sufficiently accurate for scholars, is as follows:

Two stations, each provided with a telephone, are chosen one or two miles apart, which we may call A and B. The observers will each need a magnetic compass and an anglemeter or other clinometer. They discuss per telephone which cloud is to be measured among those visible to both observers. Then they take the angular height and direction (see Fig. 110).

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[1] Quayle, *Weather Bulletin* No. 12, Melbourne.

Suppose the data obtained were as follows :

	To cloud		*To cloud*
Station A.	Direction N. 77° E.	Station B.	Direction N. 9° E.
	Altitude 20°		Altitude 30°

Line A B is 74° east of south.

We can readily plot these angles and so discover the height.

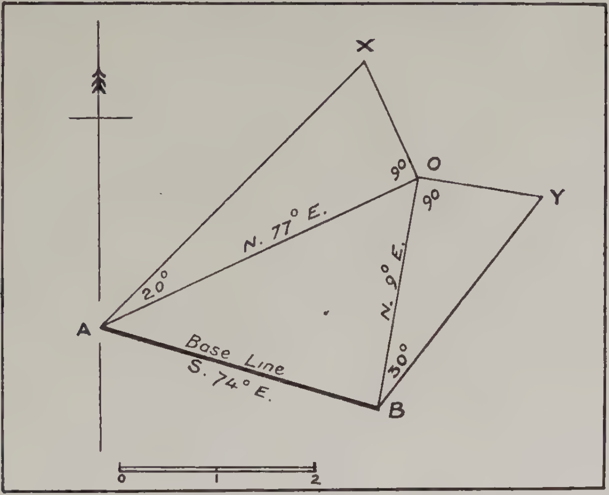

Fig. 110. A simple method of determining cloud height.

First draw base A B to scale and in the proper direction. Then set out the directions to the cloud A O and B O. These intersect in O, which must necessarily be vertically under the cloud. Now lay off A X at 20° from A O and draw O X perpendicular to A O to meet A X in X. Then O X is the required height to scale and is found to be 7,000 feet. (We could find O Y with the same result.)

We can imagine the triangle A O X rotated about A O so that O X is vertical, and the triangle B O Y rotated similarly about O B. Then X and Y will coincide at the position (to scale) of the required cloud.

Measurement of Cloud Velocity

Several forms of nephoscope are in use at weather bureaux, but a simple form (modelled on Besson's pattern) is described by Mr. Quayle and can be made and used by any student (Fig. 111). The problem is to determine the time taken for a cloud to pass across a given angular distance—usually 15°. (Of course the cloud is here assumed to float at the *average elevation* for its type.)

A T-shaped piece of wood is constructed with the long arm 25 inches in length (and say 1 inch wide). A thin strip 6·58 inches long is fastened across this at one end. Under these circumstances the cross-piece subtends 15°

with regard to the eye. If now the end be placed against the cheek bone close to the eye, the crossbar can be pointed at the cloud and rotated until the cloud be moving along the crossbar.

Clouds near the zenith (i.e. overhead) should be chosen; and the time taken for the cloud to pass along the crossbar (i.e. 15°) can be determined. It will be convenient to insert two nails into the crossbar and so subdivide it into 5° sections.

The direction may now be determined by using the T-stick to measure the horizontal angle from a predetermined cardinal point. For *cirrus* work it will be found convenient to have the direction *due west from the station* indicated by some distant fixed point; and then measure the angle from this datum.

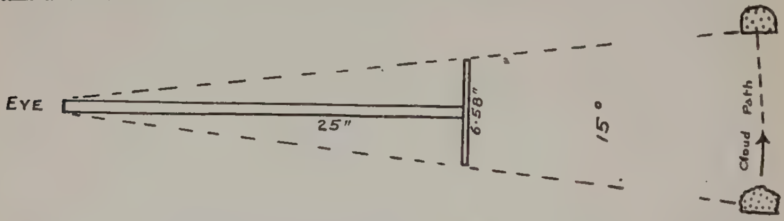

FIG. 111. A simple nephoscope devised by E. T. Quayle to determine the angular velocity of clouds.

CIRRUS MOVEMENTS. During the last ten years the attention of meteorologists has been turned more and more to phenomena occurring at the level of the upper clouds, which float about six miles above sea level. Hereabouts is the 'isothermal layer' which is described in detail later. Events hereabouts seem to control all that goes on in the atmosphere below almost to the surface of the earth. The only clue which we have to the air movements in this region is afforded by the cirrus, apart from occasional balloon investigations. Hence the drift of the cirrus is well worth observation, and it has been specially studied by Mr. Quayle in Melbourne for many years.[1] I shall quote freely from his research.

The mean direction of the cirrus at Melbourne is almost exactly from the west. But during the year it varies somewhat between W. 17° N. in August to W. 7° S. in February (see Fig. 112). Favourable (wet) seasons in Melbourne are almost always those when the cirrus drift is from a more northerly direction than the normal. 'Good winter rains, at all events over the northern parts of Victoria, follow summers in which the flow of the upper air is more decidedly polewards than usual.' (See also the chapter on Forecasting.)

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[1] 'Cirrus Directions and Forecasting', Quayle, *Bulletin* 10, Melbourne, 1915. See also *Weather Reports* for December 1910 and for the year 1912.

Height and Latitude. The heights and velocities of the clouds vary with latitude and with the season. Hann gives an interesting table for various latitudes which is quoted below.

Summer Mean Height of Clouds (in Kilometres)

Latitude	78½ N.	60 N.	42½ N.	25½ N.
Cirrus	7·3	8·9	9·5	12·4
Strato-cumulus . .	2·5	2·3	1·2	3·5

In winter the cirrus is about 1 kilometre lower in elevation. The velocity of the cirrus is usually from 50 to 70 miles per hour (22 to 30 metres per second); whereas the lowest clouds only travel 15 miles per hour. Generally speaking the velocity is greater in winter than in summer.

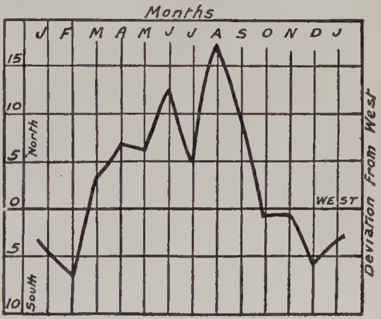

Fig. 112. Average monthly cirrus directions at Melbourne. (Data by Quayle.)

Amount of Cloud. The *Observers' Handbook* advises observers to subdivide the sky mentally into quadrants. An estimate is then formed for each quadrant separately. If the whole is overcast its scale number is 10, if half overcast 5, and so on. The figure finally entered in the register is the mean of the four numbers so obtained.

The amount of cloud—during the day—can of course be estimated from the amount of sunshine. In Fig. 113 I have plotted the two graphs for Perth, and the relation is seen to be extremely close. The seasonal distribution of the cloud is the same as for the rainfall, so that Perth is most cloudy in winter and Brisbane in summer, while Hobart, with a fairly uniform rainfall, is also uniformly cloudy through the year.

Sunshine Recorder. The amount of sunshine is usually only measured at the most important weather stations. The Campbell-Stokes instrument consists of a glass sphere about

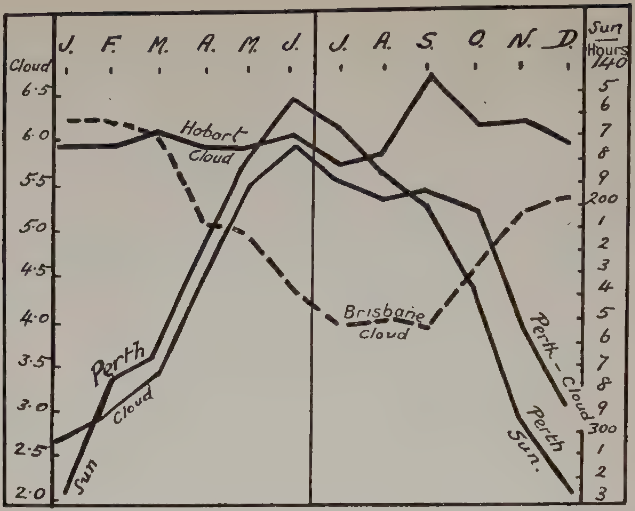

FIG. 113. Cloud data for Brisbane, Perth, and Hobart. (Maximum=10.) The hours of sunshine for Perth are also plotted and the graph of course is the inverse of the other graph.

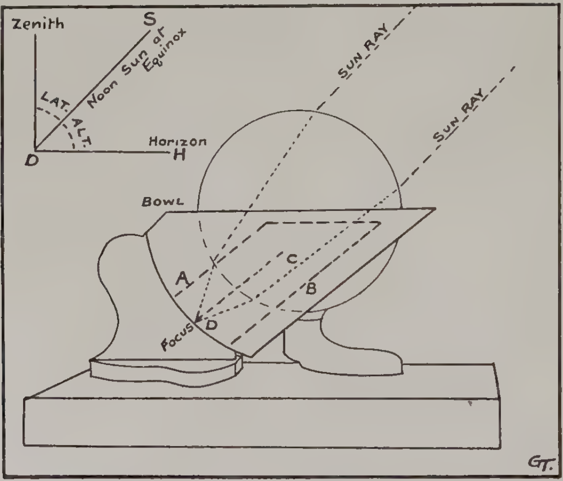

FIG. 114. Campbell-Stokes sunshine recorder. The sun's rays pass through a glass ball and are focussed on cardboard, which they burn. The metal segment of a bowl, carrying on its inner face the cardboard belt AB, is shown as if transparent. The broken black streak (from C to D) shows how the sun increases in vigour as noon is reached—for the burnt patches grow larger. The position of the cardboard with regard to the rays depends on the latitude, the principle being shown in the sketch at the side.

3 inches in diameter, which acts as a lens to burn a record on a cardboard sheet placed at its focus. The cardboard is mounted on a curved metal surface and is arranged to suit the latitude of the station, for this determines the altitude of the sun.

In Fig. 114 the apparatus is so adjusted that the mean solar ray at noon will be at about 45°. This average inclination should correspond to the mean altitude of the sun—which occurs of course when he is over the equator. At the equinox the sun's noon altitude at any place is equal to the co-latitude (90° *minus* the latitude). Hence our apparatus (Fig. 114) is suited for latitude 90°−45°=45°. For Melbourne the altitude (SDH) for the *average* noon ray should be 90°−38°, or 52°.

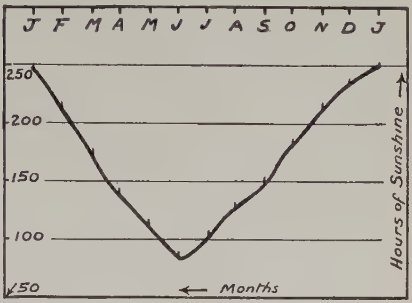

FIG. 115. Hours of sunshine through the year at Melbourne. From the Stokes recorder. (This does not record feeble sunshine.) See also Fig. 113.

The apparatus is set up so that the line joining the centre of the sphere to the centre of the cardboard record lies on the *meridian* of the station. At the same time this line must make an angle with the horizon equal to the *mean altitude* of the sun, for reasons given above.

The monthly variation in the hours of sunshine depends largely on the declination of the sun, i.e. on his angular distance from the equatorial plane. In Fig. 115 the hours of sunshine are plotted for the various months at Melbourne. The graph rises to a maximum at the end of December and falls to a minimum at the end of June—which are the times when the sun is farthest south and farthest north respectively.

In less sunny regions, or those with a less uniform rainfall, considerable variations exist. Milham's table[1] shows that most places in U.S.A. have most sunshine in summer. But Los Angeles in California has its maximum (80 per cent. of the possible) in winter (December) and its minimum (60 per cent.) in May, in spite of its rains occurring chiefly in winter.

The greatest average cloudiness is naturally where the air is on the whole ascending. Hence the three low-pressure belts in the world are all cloudy. The arid regions are similarly the least cloudy. In Australia the cloud belts agree with the rain belts fairly closely.

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[1] Milham's *Meteorology*, p. 230.

CHAPTER XIV

RAINFALL

The element above all others with which the Australian meteorologist is concerned is the rainfall. The whole prosperity of the country is bound up with the amount of rain, its distribution, and its seasonable fall. The dread enemy who has ruined thousands is King Drought. Frost hardly touches us at all. Floods are only occasional and their damage is localized, but the rains and their characteristics are discussed in 90 per cent. of Australian meteorological literature.

Raindrops. The actual conditions accompanying the formation of drops of rain are not fully understood. Occasionally one sees rain falling from a clear sky, without the formation of a cloud. Such rain is always small in amount and soon over.

Possibly changes in the electric charges may help to increase the size of the drops, but this is not so probable as the theory that there is a local circulation in a large cloud. Thus the upper layer (according to Reynolds) will cool more rapidly, and so larger drops will form and descend, being replaced by others. Hann doubts whether drops grow by accretion after they leave the cloud. The latent heat thus set free in the drop suffices to bring the condensation to a standstill.

Size of Raindrops. This has been investigated very fully by Bentley in U.S.A.[1] He collected the raindrops in flour and measured the resulting spheres of dough, with most interesting results. The drops vary greatly in size, the most numerous being between $\frac{1}{30}$ and $\frac{1}{18}$ inch diameter. There were only 35 drops out of 344 over $\frac{1}{5}$ inch diameter.

All the 'very large' drops and most of the 'large' ones emanated from compound cloud masses whose vertical dimensions are very considerable. Low-level cumulus 'nimbus' and high-level cirro-stratus, &c., give only small drops, but intermerging cumulus and cirro-stratus are often heavy rain producers. When lightning discharge is frequent the raindrops are larger. [The phenomena may be due to a common cause, and it is not certain that the discharge produces the large drops.] The raindrops probably decrease as they fall as the result of evaporation and erosion.

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[1] Bentley on Raindrops, 1904; U.S.A. *Weather Review*, pp. 450–7.

Bentley found many cases of storms with uniform raindrops. He is led to believe that these represent melted snow crystals or granular snow, since from ordinary clouds the drops are normally very variable in size. ‘The region of maximum precipitation varies in altitude; but in general the altitude is so great that it is quite certain that much of its moisture is precipitated in the form of snow.’ This is also true of thunder showers.

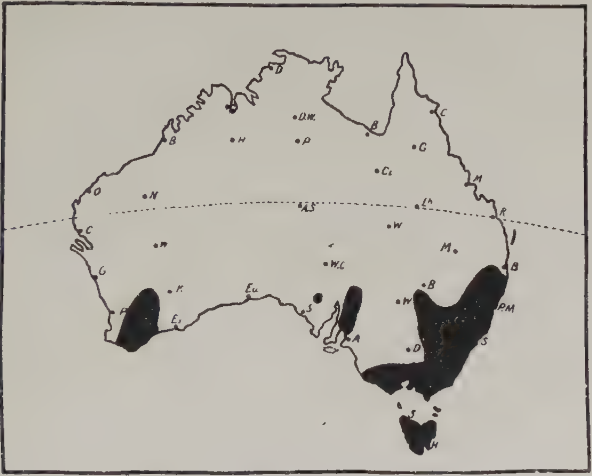

Fig. 116. Regions where snow has fallen (H. A. Hunt).

Snow is formed when the water vapour is condensed below the freezing-point. It is composed of minute hexagonal crystals of ice often collected into ‘fluff-balls’ or flakes. The simple crystals are either hexagonal disks or hexagonal columns. Many of the optical effects of the polar regions are due to the perfect form of these small floating crystals. They act as mirrors and so give rise to mock-suns. Haloes are of somewhat similar origin.

Snow may fall at all temperatures between −40° F. and +50° F. (Hann), but in Australia the temperature is usually round about 32° F. (see Fig. 116).

Distribution of Snow in Australia. H. A. Hunt gives some interesting data in *Meteorological Bulletin* 9 (1914). 'During the winter snow can always be expected along the mountain ranges in New South Wales, Victoria, and Tasmania, and occasionally on the Mount Lofty ranges in South Australia. On rare occasions also it has reached as far north as Toowoomba in Queensland (lat. 27½° S.). The heaviest snowstorm on record in New South Wales occurred between 3 and 7 July, 1900, extending from the Hunter river to Condobolin. In places the snow was 8 feet deep on the railways, and at Bathurst many roofs collapsed under its weight.'

Other noteworthy falls were on 28 July, 1901, and on 29 August, 1905, both of which extended throughout south-east Australia. Heavy falls are almost unknown at Sydney and Melbourne. They are recorded in 1836 (Sydney) and 1849 and 1899 (Melbourne).

In Tasmania snow falls throughout the year in the highlands. In the settled lowlands it is rare from October to February. In May 1915 about 6 inches fell throughout the midlands, which was said to be the heaviest fall for many years.

Glacial erosion has left its traces around Kosciusko and Cradle Mountain (Tas.). Occasionally great snow drifts of *nevé* last to the end of February (i.e. through the hottest weather) on the sheltered east slopes of Kosciusko. This was the case in 1907. In winter ski-ing, sleighing, and tobogganing are very popular around Kosciusko, Buffalo, and other tourist resorts; and at Kiandra (N.S.W.) snow-shoes have been in use for many years.

CHANGE OF STATE. We have learned that water can exist in many states—as ice, hail, or snow; as liquid and as vapour. A body of moist air as it rises from sea level may pass through any or all of these states, and it is necessary to examine what occurs. The complete theory is very complicated; but Waldo gives a graph and an explanation (based on Hertz) which it is not difficult to follow (see Fig. 117).

A special 'network' is used for the graph, where the ordinates are temperature (Centigrade) and atmospheric pressure (in millimetres). This pressure is converted into metres of elevation on the left of Fig. 117. Saturation lines for differing amounts are drawn diagonally, of which three (for 22 grams of water per kilogram of air, 11, and 6 grams) are indicated.

Now suppose we have at sea level a kilogram of air with barometric pressure 750 mm., a temperature of 27° C., and a relative humidity of 50 per cent. This air ascends, and it is desired to know the changes it undergoes and the conditions as it passes from vapour to rain, &c.

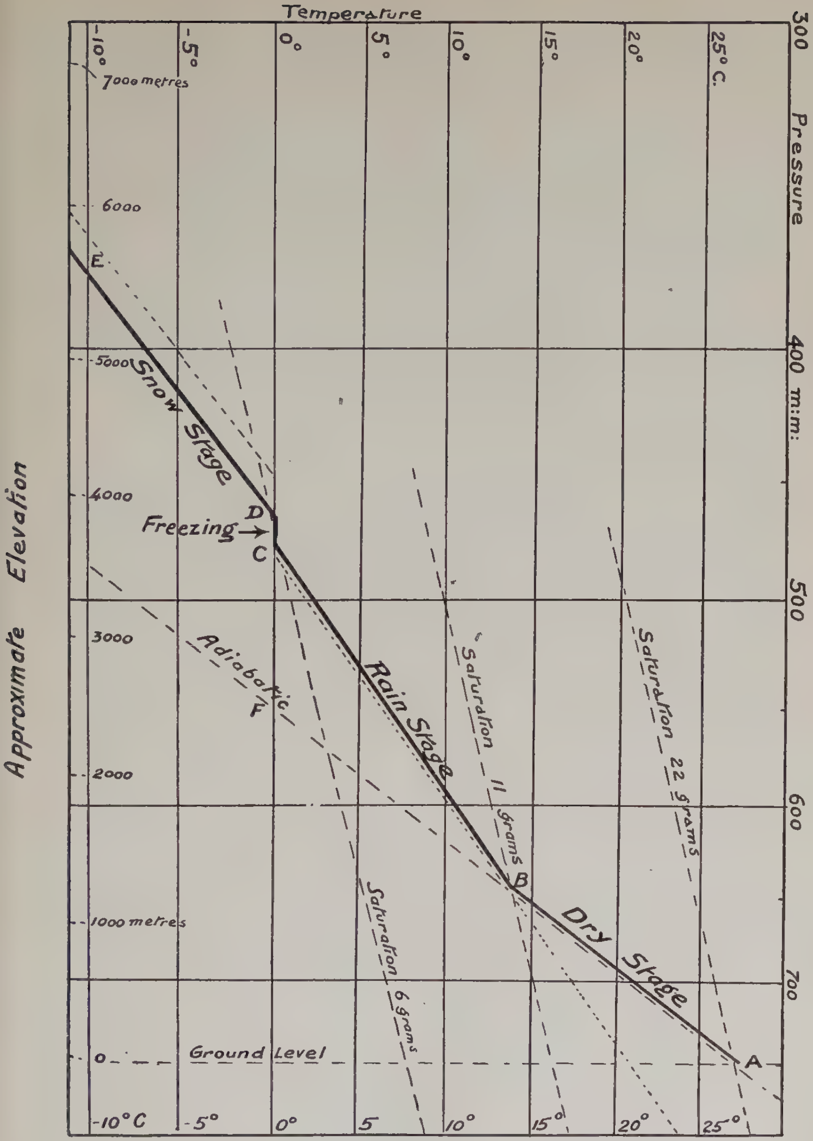

FIG. 117. An approximate graphical method of showing the 'changes of state' in rising moist air (after Hertz and Waldo).

Let A (on Fig. 117) be the position of the air at starting. It is seen that if it were saturated it would contain 22 grams, but being only half saturated its *absolute* humidity is 11 grams (by hypothesis).

Now let the air mass be gradually elevated. Its temperature and pressure will fall, and it can be graphed as moving along a line A B, which fulfils all the conditions that occur (and is known as an *adiabatic* line). At B the 11 grams saturation line is reached, when it has cooled to 13° C. Here it reaches its saturation level at about 1,300 metres. Hereafter vapour is gradually condensed and the air cools much less rapidly. It now follows along the line B C and is traversing the rain-stage until it rises to 3,700 metres or so. Here it has cooled to the freezing-point 0° C. [For *dry* air this temperature would have been reached at about 2,600 metres, as is seen by following the adiabatic A B to F.]

At C the 6 grams saturation-line is reached, so that 5 of the original 11 grams have now been condensed as water. The remaining water now freezes and there is no change in temperature while this is occurring, though the pressure and elevation change as shown. After D the snow-stage begins and the snow-cloud continues to cool as it ascends, as shown by the line D E.

MEASUREMENT OF RAIN

Rain gauges in Australia consist of a cylinder of galvanized iron about 1 foot high with a stout brass rim of 8 inches diameter. A funnel with a central opening shuts off the upper 3 inches of the gauge. The rain is measured in a graduated glass measure, and the record is entered in *points*, 100 points equalling 1 inch.

The gauge should be placed on a level piece of ground, not upon a slope, wall, or roof. It should not be nearer to an obstacle than twice the height of the latter. In Australia the gauge is mounted in a stout box which is firmly bedded in the earth.

The rainfall is read at 9 a.m. and the record is entered against that date. Obviously this record gives the rainfall for the preceding twenty-four hours, and this should always be borne in mind when studying the relation between rainfall and pressure or temperature changes.

SELF-RECORDING RAIN GAUGE. There are many patterns of pluviograph in use, but one of the best is the siphon type as improved by Hellmann. The essential features are shown in Fig. 118. From the gauge the water runs into a float chamber and raises a float. When the water has risen to a convenient amount (equal to 40 points of rain), it is released by the siphon overflow and flows into the collector below.

Attached to the float is a piston or rod which rises vertically and carries a pen. This marks the height on a chronograph of the usual type. The record consists of a series of 'teeth', each representing 'one filling' of the float-chamber (i.e. 40 points of rain). The record can be seen on the chronograph drum in Fig. 118.

Rain-gauge Errors. The measurement of rain would appear to be a simple matter; yet it is very difficult to obtain true comparable records. The effect of wind is very striking. Thus the work of Phillips and Gray at York Minster show that only about half as much rain is recorded in a gauge on the tower (220 feet) as on the ground below. This is due to the wind forming eddies over the rain gauge and depositing much of the rain on the lee side. The stronger the wind (as on a high tower), the greater is the percentage lost. Abbe says the percentage departure from the true amount varies as 6 $\sqrt{H}$, where H is the altitude. Thus a height of 25 metres would mean a loss of 30 per cent. of the rain. (*Vide* Hann.)

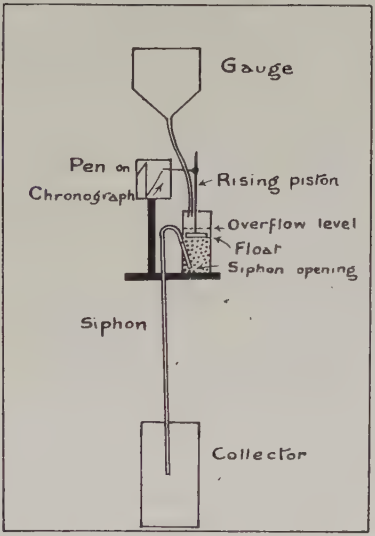

Fig. 118. The principle of the Siphon Recording Rain Gauge (the framework and case omitted).

Some gauges are fitted with Nipher's shield, which is a wire frame like a funnel round the rim. It breaks up the wind and deflects it downward from the rim.

Rainfall Data. In Australia the chief rainfall records deal with the annual total, and the monthly totals. But there are many other features which are of interest, and which are 'taken out' at the chief climatological stations. Thus the hourly and daily rainfall, the number of rain days, the greatest rainfall in 24 hours, the periods of drought, and many other variations, are generally tabulated.

A reference to Fig. 119 will enable us to see how the rainfall varies from month to month and from place to place. Here are shown the monthly rainfalls for ten years at Sydney, Perth, and Burketown (on the Gulf of Carpentaria). As we shall see, each locality is characterized by special features.

For Sydney the years 1881 to 1890 are plotted. The vertical ordinates represent *monthly rainfall*, the horizontal ordinates are the *twelve months* (repeated ten times).

If we follow along the zig-zag line which records the monthly rainfall we see that it fluctuates greatly. Some features are fairly evident, however. The rainfall is greater in the first half of the year than in the second half. If we average the monthly rainfalls we get the curve O P Q R (reproduced as the broken line in each year). It is obvious that the actual rainfall rarely agrees with the average rainfall, but the discrepancies are not so great as in most other localities in Australia.

The average total rainfall at *Sydney* is 48 inches per annum. The average monthly graph therefore lies equally above and below the line A B, which is at 4·0 inches (i.e. 48 by 12). The maximum monthly rainfall in the period charted is 20·9 inches in May 1889; and the minimum is 0·04 inches in August 1885. (In the same year is shown the June record maximum for Sydney of 16·3 inches). The wettest year shown is 1890 with a total of 81·4 inches. This was only beaten by 1860 with 82·8 inches in the Sydney record. In 1888 only 23 inches were received, which is almost a record for the locality (21·5 inches in 1849). Hence the decade illustrated was a very variable period in the rainfall history of Sydney.

The second locality charted is Perth in West Australia. This differs in type considerably from Sydney. The rain obviously falls almost wholly in winter; secondly, the variations from the normal rainfall are very much less. In 1890 we see the wettest year recorded at Perth with 46·7 inches. The average annual rainfall is 33·2 inches, and this was recorded (within an inch or so) in 1891, 1892, 1895, 1896, 1898, and 1899. In 1894 is given

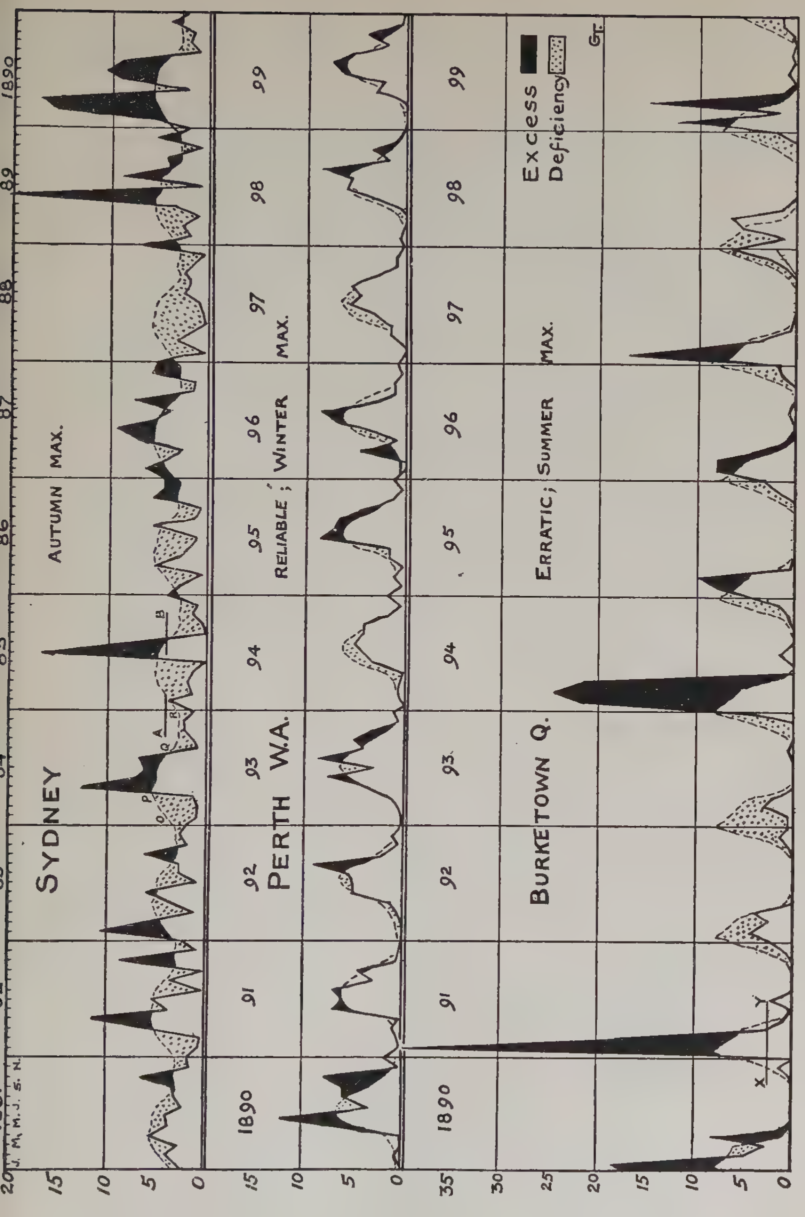

FIG. 119. Three typical stations and their monthly rain graphs for ten years. Sydney has an autumn maximum; Perth has reliable rains with a winter maximum; Burketown has erratic rains with a summer maximum.

almost the driest year at Perth with 23·7 inches. (The record is 1877, with 20·5 inches.) Hence the variation is remarkably little, and indeed Perth has the best rainfall in Australia in this respect (see Fig. 125).

The third locality illustrated is remote from either of the other two cities. It is Burketown, on the southern shore of the Gulf of Carpentaria. Here the average rainfall is 28·2 inches a year, and this figure divided by 12 gives 2·4 inches per month, which is shown by the line X Y.

Here again two features are obvious. The rainfall occurs wholly in summer, and the variability is extreme. Thus in January 1891 there fell 40 inches, in January 1892 only 4 inches, in January 1893 less than ½ inch, to be followed by 22 inches in January 1894. What a hopeful region is this for the agriculturist! Here we have the wettest year on record (1894, with 76 inches) succeeding almost the driest on record (1893, with 11 inches).

ANNUAL RAINFALL OF AUSTRALIA. The first rainfall map to be compiled is usually that showing the average annual rainfall. This is given in Fig. 120 and merits careful study, since it is the primary factor controlling our present industries and future progress.

The largest areas receiving a *moderate rainfall* (over 30 inches) are along the north coast. The remaining areas are only three in number. A narrow fringe extends along the east coast and is about 100 miles wide. The western half of Tasmania is also wet, and the extreme south-west corner of the continent near Cape Leeuwin is also moderately wet.

The area with a quite inadequate rainfall (under 10 inches a year) is confined to the temperate region. The latest records make the 10-inch *isohyet* (line of equal rainfall) run along the Tropic of Capricorn from North-West Cape to Boulia in Queensland. Thence it turns south to Wentworth on the Murray. Here it bends to the west and proceeds to the Norseman goldfield (in W.A.). Thence it turns to the north-west to Shark Bay.

In Fig. 120 I have plotted also the isohyets for 8 inches, 6 inches, and 5 inches. They are not very accurate, for several reasons. In the west is a large tract (equal to New South Wales and Victoria combined) without an inhabitant. Here are no gauges, and so the isohyets are only drawn tentatively. Secondly, the records are somewhat short in many of the localities, especially in view of the very erratic character of the rains hereabouts. However, it seems fairly certain that the driest region in Australia surrounds Lake Eyre.

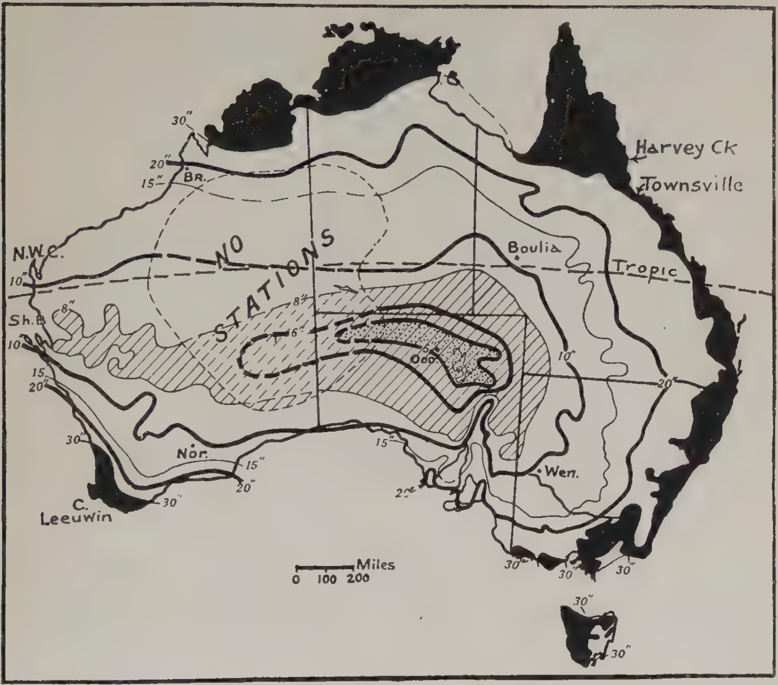

FIG. 120. Average annual rainfall of Australia, revised to 1916. Over 30 inches shown black; the driest region (under 8 inches) is ruled. (The records in central West Australia are still too short for accuracy.) (Partly based on Hunt.)

The following table gives the driest localities so far as our records show.

MOST ARID STATIONS IN AUSTRALIA

	Position.	*Average Annual.*	*Years of Record.*
Mulloorina .	South shore of Lake Eyre	4·07	21
Kanowana .	120 miles east of Lake Eyre	4·24	20
Oodnadatta .	90 miles north-west of Lake Eyre	4·68	24
Murnpeowie .	70 miles south-east of Lake Eyre	4·79	23
Mungeranie .	80 miles east of Lake Eyre	4·89	18

In Fig. 121 is shown the distribution of the isohyets in two extreme rainfall regions in Australia. From the lower figure one would expect that the driest spot would be where the Diamantina river enters Lake Eyre. We have no station here; and so Kanowana is the driest station. But with a highly erratic rainfall such as falls here, probably fifty years' record will be necessary to decide the record. The aridity is directly due to the fact that Lake Eyre lies too far south for the summer rain storms and too far north for the winter rain storms to benefit it. Occasional thunderstorms are the chief rain producers. The controlling factors will be best understood from a study of the solar control model, described in a later chapter.

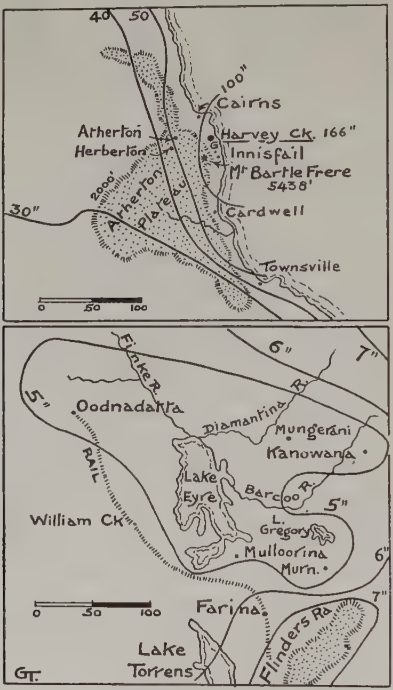

FIG. 121. Maps of the wettest and driest regions in Australia. (Highlands dotted.)

The wettest region in Australia is on the eastern scarp of the Atherton Plateau in Queensland (see Fig. 121).[1] Here the moist onshore winds rise from 3,000 to 5,000 feet and are cooled more than 10° in consequence. The south-east trade wind is nearly permanent, and the rains are almost continuous. The following table shows the average figures for sixteen years at Harvey Creek (in inches).

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[1] The topographic control of Rainfall is very important and is discussed in the climatic chapter.

Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year.*
30·9	22·2	32·2	22·2	13·2	8·0	4·2	5·4	3·7	3·8	8·1	11·7	165·6

Some remarkable falls within twenty-four hours have occurred on this coast near Cairns, and are given in the following table. It is taken from the official *Rainfall Observations made in Queensland,* Hunt, 1914.

Exceptional Rainfall in Twenty-four Hours

Inches.	*Locality.*	*Date.*
31·53	Port Douglas	1 April 1911
28·30	Kuranda	2 April 1911
27·75	Harvey Creek	3 January 1911
24·72	,, ,,	31 January 1913
24·10	Goondi	30 January 1913
23·33	Macnade	6 January 1901
21·22	Innisfail	23 December 1903

Rainfall in States. We may now see how the various States compare *inter se* as regards the total amount of rainfall. For reasons which will be obvious later, the temperate and tropical regions are separated.

The Chief Asset of Australia—the Rainfall

(Approximate areas in square miles.)	*Temperate Regions.*			*Tropical.*		
	Over 20″.	*20–10″.*	*10–4″.*	*Over 20″.*	*20–10″.*	*Total.*
New South Wales	130,468	134,907	44,997	—	—	310,372
Queensland . .	132,000	120,000	60,500	240,000	118,000	670,500
West Australia[1] .	69,000	83,000	493,120	105,800	225,000	975,920
Victoria . .	55,346	32,538	—	—	—	87,884
South Australia .	14,875	47,595	317,600	—	—	380,070
Tasmania . .	25,278	937	—	—	—	26,215
Northern Territory	—	—	138,190	180,940	204,490	523,620
	426,967	418,977	1,054,407	526,740	547,490	2,974,581

It is this first column which will very largely determine close settlement. Mere inspection shows that South Australia with a larger area can never approach New South Wales as a primary producer, while Northern Territory must wait till the other regions are feeling the struggle for existence before it can command anything like a notable population. The high place of Queensland is noteworthy. It certainly gives promise of greater development than any of the other States. This aspect will, however, receive closer attention in a later chapter.

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[1] See Appendix I for details of S.E. Australian Rainfall.

CHAPTER XV

THE MONTHLY MARCH OF THE RAIN BELT

In a map showing the annual rainfall of the continent the isohyets form approximately concentric ovals around the arid centre of the continent. This arrangement does not, however, mean that the coastal regions are always wet; although unfortunately it is true that the interior is nearly always dry. As we shall see, in each month the region with over 1 inch of rainfall forms a somewhat 'crescent'-shaped area, whose concavity lies toward the centre. These 'crescents' slowly swing round from north, through east to south, and then back again during the year.

Let us now consider the months in some detail.

Early in January the sun is practically at its farthest south point and the monsoon is at its height. The cold Tibetan plateau and warm centre of Australia act in unison to produce a constant sequence of low-pressure areas in northern Australia, and hence an average of ½ inch of rain falls each day at Port Darwin, gradually decreasing towards the south. Alice Springs (in the centre) gets about 1 inch in the month, while south and south-west Australia receive practically no rain.

In February the rain belt is less intense at Port Darwin (the monthly fall being 10 inches instead of 15 inches), but otherwise the distribution over the continent is much the same.

In March the summer rains have retreated still farther north, and the southern limb of the 'crescent' is beginning to cover the south-west coast. (The south-east trades have given the Queensland coast near Cairns over 20 inches during each of the three months considered.)

In April the winter rains are beginning to be felt along the whole south coast, though only to the extent of an inch or so during the month.

In May the southern type of rainfall is in full swing and no rain falls in the north. The 'crescent' has now tilted round, and opens to the north so that its two limbs cover the east and west coastal areas.

In June, July, and August, similar conditions obtain; the rain belt (over 1 inch) having still the shape of a crescent and covering the coast from North-west Cape around the south and up the east coast to Cooktown.

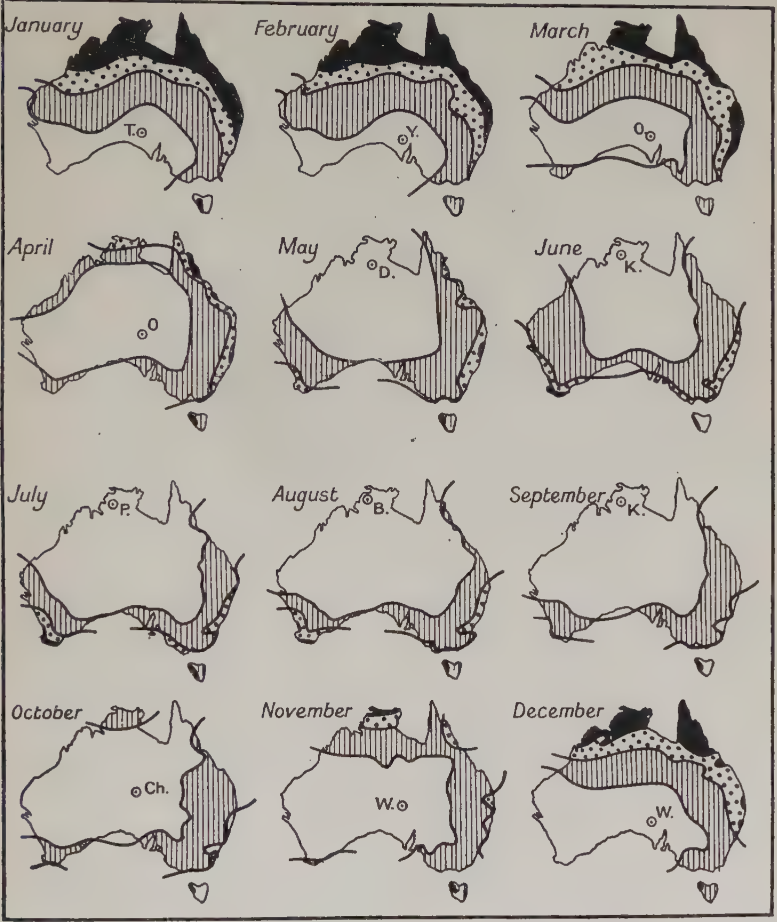

Fig. 122. March of the monthly rainfall (isohyets after H. A. Hunt). Black over 5 inches; dotted over 3 inches; white under 1 inch per month. The small circle shows the driest locality each month. (See Table, p. 151.)

September is perhaps the driest month in the year—if we consider Australia as a whole. Only the extreme south-west corner of Tasmania and the Cordillera region in the south-east have a rainfall of over 2 inches. The southern rains are now moving south as the sun retraces his path from his northern limit.

In October there can hardly be said to be a rain *belt*, for the rain region is divided into three isolated areas. The northward bulge of the southern ocean in the Bight has severed the winter rain area in two, while in Northern Territory the summer rains are again creeping southward and are giving that settlement over 2 inches. For six months (since April) the north-west coast and York Peninsula have had practically no rain.

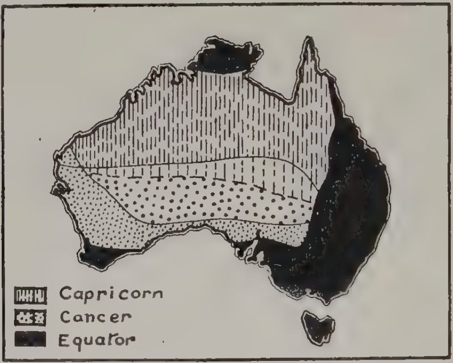

FIG. 123. Solar control of seasonal rainfall. Broken lines show rains due to sun's path south of equator to and from Capricorn. Dotted areas show rain due to sun's path north to and from Cancer. Black areas show rains when sun is on the equator.

In November the winter rains are over. The 'crescent' turns toward the north-east again, and the monsoonal rains are dominating the north of the continent. In December the summer rain has reached Alice Springs in the centre of the continent, and over an inch has fallen in that region.

THE SUN'S CONTROL OF THE RAIN BELT. If the earth's axis were perpendicular to the plane of the ecliptic, the tropical rains would hardly reach south of Darwin, and in the west only the extreme south-west corner of Western Australia would project beyond the central desert (see Fig. 123).

The effect of the inclination of the earth's axis is to cause the sun to appear to move[1] from tropic to tropic in each half year, and it is this movement—or change in declination—which controls all our seasonal changes. All the isotherms, isobars, and isohyets, with their attendant winds, storms, and rains, move north and south in unison with the swing of the sun.

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[1] It is convenient to assume that the sun is moving, rather than the earth.

This annual path of the sun covers 47 geographical degrees, or over 3,000 miles in the course of six months. Its poleward rate is of course greatest over the equator, so that at the equinoxes the sun is each hour moving about *one mile north* (or south) while it moves 900 miles to the west.

Let us see how the chief meteorological elements follow the path of the sun. In the case of Temperature we may take the isotherm of 70° as an index; during the six months January–July it moves north from Port Lincoln to Daly Waters, a distance of 1,350 miles. In the case of Pressure, using 29·90 as an index, we find it swings from Streaky Bay (January) up to Darwin (July), almost exactly the same distance.

As regards rainfall the swing is somewhat less, as was to be expected, since the principle of inertia includes a 'lag', which increases with the length of the chain of controls involved.

Confining our attention as before to the central belt (where the direct solar effect is best marked) we may tabulate the position of the driest locality in each month (see initials on Fig. 122).

Driest Places in Each Month

Month.	*Locality.*	*Latitude.*	*Rainfall. Pts.*
January . .	Tarcoola	31° 30′	24
	(Coward Springs	29° 30′	23)
February . .	Yudnapinnie	32°	31
March . . .	Oakden Hills	31°	36
April . . .	Oodnadatta	27° 30′	20
May . . .	Daly Waters	16°	16
June . . .	Katherine	14° 30′	8
	(Pine Creek	14°	6)
July . . .	Pine Creek	14°	5
	(Katherine	14° 30′	3)
August . . .	Broch Creek	13	1
September . .	Katherine	14° 30′	27
	(Charlotte Waters	26°	17)
October . . .	Charlotte Waters	26°	30
	(Oodnadatta	27° 30′	28)
November . .	Warrina	28° 10′	35
December . .	Wilgena	30° 40′	34

I have plotted these figures on the graph shown in Fig. 124. A smoothed curve drawn through the positions is quite symmetrical, except in September. In this month there are two dry patches, one centred at Katherine and another at Charlotte Waters, and the former of these lies on the curve.

The sun's declination is shown on the same graph—of course to a different latitude scale. The two chief features are well brought out here: firstly the lesser amplitude of the rainfall swing, 20° as compared with 46°; and secondly the 'lag', which is seen to amount to about five weeks.

In Fig. 123 the vast importance of the solar swing is shown as a map. The black areas show the regions receiving rain when the sun is overhead at the equator. If it remained in that position, i.e. if the plane of the ecliptic coincided with the equator, there would be hardly any rain received elsewhere in Australia. But during the sun's movement from the equator to the tropic of Capricorn the region shown by close vertical lines receives copious rains, while where the lines are farther apart, they are less abundant. Similarly when the sun moves northward from the equator to the tropic of Cancer and back, the southern inland belt receives its rain (as before, the stippling roughly indicating the division between good and poor rains).

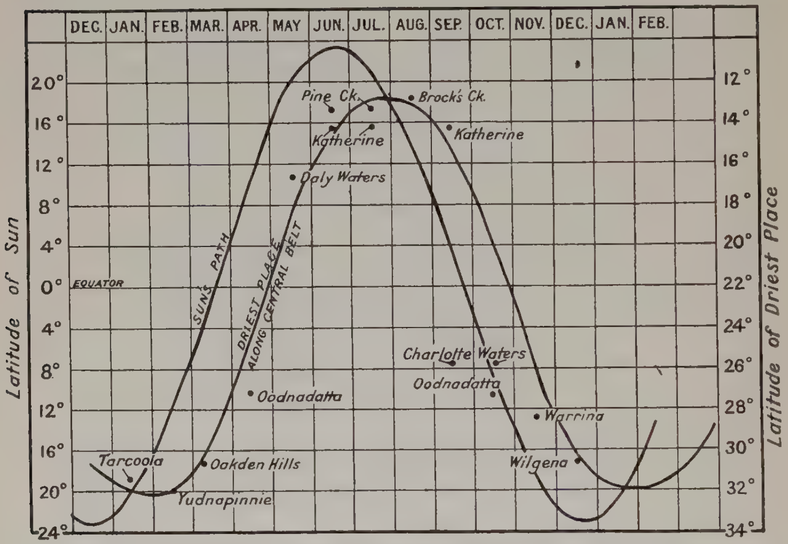

FIG. 124. Relation of sun's march between tropics to the march of the rain belt. (Driest spot in each month being used as index.)

In the latitude graph (Fig. 124) the 'driest locality' is due to its coming most strongly under the influence of the desiccating south-east winds. These, as stated, move along the northern limb of the Highs. The axis of the Highs—or the path along which the centres of the Highs move—is therefore a very important locus, and varies from month to month. These loci are shown in Fig. 64, and these lines form a very logical and convenient index for the model about to be described.

THE SOLAR CONTROL MODEL.[1] Australia has one great advantage from the point of view of the climatologist—that it offers the widest stretch of low and level land in the world, which is affected by the trade wind. The Sahara is similarly situated, but is not so favourable topographically, while the meteorological information available is negligible. Hence some of the main processes are offered to us in Australia in their least complex form, and chief among these is the seasonal rainfall.

The solar control model is indeed almost self-explanatory. The various processes involved have already been discussed. The solar swing causes temperature and pressure swings—the two latter being almost equal in amount—and also on these depends the rainfall swing of slightly less amplitude. We may, however, assume that the pressure and rainfall swings are equal, as the ratio is about 1,350 to 1,200.

At the top left corner of the model (see Frontispiece) the swing of the sun from tropic to tropic is indicated. In the main body of the model, on a larger scale, is shown the swing of the anticyclone axis. In midsummer this passes through Melbourne, and in midwinter from Perth to Brisbane. Associated with this axis is the belt of variable winds immediately on each side, and farther away lie the trade wind belt on the north and the belt of permanent westerlies on the south.

Associated with the trade wind belt is the arid area of the continents, and this is shown as a flask-shaped area with the opening to the west. On the model the 1-inch and 2-inch isohyets are shown in a somewhat generalized fashion, which is, however, little removed from the actual monthly limits, as the working of the model shows.

The model departs from the theoretical flask-shaped 'arid area' (which is usually shown on *generalized* vegetation maps) chiefly in the Onslow-Nullagine region; where a slight bulge is inserted (on the 1-inch isohyet on the sliding card) so that the model will agree with actual rains. This is the least reliable of our rain provinces, and the records are not very long, so that this bulge may be partly due to some such abnormal rains as in April 1900, when 20 inches fell instead of the average amount of one inch. The rains in this region, though seasonal, are less simply connected with the solar swing, and are associated with the well-marked summer Low of the north-west. The latter is not centrally situated, and so disturbs the general symmetry and regular march of the climate in Australia, as we shall see later.

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[1] Given as Frontispiece.

The main meteorological phenomena of Australia are therefore shown at a glance in this model, and we may now run through the history of the year. But it must be remembered that the rain belt follows the sun after a 'lag' of some five weeks. Hence the effect of the farthest distance (north) of the sun is experienced at the end of July, and the equinoctial effect in October and April.

The sun is on the equator at the end of September—adding five weeks this means the end of October; and if we move the sliding card so that the sun is opposite the equator, we see that the line of the centres of Highs runs from Leeuwin to Grafton. This axis accordingly intersects the month-scale between October and November. The rainfall for the month shows the largest dry area for the year. Its general arrangement can be compared with the black area in Fig. 116. The belt of trades dominates Australia, and only down the eastern coast is the rain belt at all important.

In November the whole of the north coast is receiving tropical rains. The summer *Low* begins to operate in the north-west, and the trade-wind belt moves south to Geraldton.

In summer the axis of the Highs passes through Melbourne. The Low dominates north-west Australia, with its clockwise wind circulation. The two regions of coastal hurricanes in the tropics are shown, along the north-west and north-east coasts respectively. The westerlies no longer prevail in the south, but variables are almost wholly in evidence.

The model shows, as we should expect, that the autumn months resemble the spring months, but in reverse order, as in the following table:

SIMILAR MONTHLY RAINFALLS

SUMMER.

	January.		
	December.	February.	
SPRING.	November. October. September.	March. April. May.	*AUTUMN.*
	August.	June.	
	July.		

WINTER.

Slight lack of symmetry is to be expected; for we have no more reason to suppose that the march of the rainfall to north or to south ends with the last day of a month, than in the case of the sun—where it occurs in the third week; but omitting the aberrant region around Onslow the parallelism is almost exact.

The hurricane season is not quite symmetrical in the two coasts, starting earlier in the west. This also is no doubt due to the disturbed conditions brought about by the north-west Low. There is no similar isobaric centre on the Queensland coast.

In May the northern rainfall is practically over, the trade winds cover Northern Territory, while the southern waters are swept by constant westerlies. In June, July, and August, the axis of the Highs passes north of Brisbane, and the winds of the southern limb of the High (the south-westerlies) are prevalent along the south-east coast.

This model emphasizes the interdependence of meteorological phenomena. Even when the winds and rains leave our coasts, we are to picture them as still holding together for some distance over the sea—though how far away is still indeterminate. In my opinion it is helpful to consider the lower atmosphere as an invisible elastic layer in which the centres of pressure with their attendant winds and rains are slowly swinging one thousand miles north and the same south during the year, while the whole moves across Australia from west to east about four hundred miles a day. Speaking broadly it is the former slow movement which determines the *climate*; while it is the latter (west to east) movement—with the local oscillations and stoppages—which controls the *weather*.

CHAPTER XVI

OTHER ASPECTS OF RAINFALL

Rain Reliability. A very slight acquaintance with Australian rainfall shows that it is much more reliable in some quarters than in others. Fig. 125 is an approximation to a quantitative representation of this variation. The annual rainfalls for twenty years (1891–1910) are tabulated, and their departures from the normal obtained in each year. These departures (ignoring sign) are then averaged, and the result is expressed as a percentage of the total rainfall. Thus at Sydney the average rainfall for 75 years is 48·5 inches. The average departure is 9·5 inches, or 20 per cent. This last figure is plotted on the chart.

The distribution presents some interesting features. The most reliable rainfall occurs in the extreme south-west between Perth and Leeuwin. Here the rains rarely vary 10 per cent. from their average amount, and the lot of the farmer should be a happy one. A variation of less than 15 per cent. from the average occurs along the south coast from Dongara (W.A.) to Cape Howe—only the head of the Bight being omitted. As regards the 20 per cent. isopleth it runs parallel to the preceding one from Northampton (W.A.) through Southern Cross, Tarcoola, to Hay (N.S.W.). Here there is a striking bulge north to the Darling Downs (Q.) and then back to Sydney. This bulge is of course due to the highlands region—as Mr. Hunt pointed out some years ago, the mountain rains are always more reliable than those of the adjacent lowlands. A narrow belt along the north coast from Darwin to Mein (Q.) also varies about 20 per cent. from its normal.

The isopleths of greater variability run concentric to the least favoured regions around Charlotte Waters (57 per cent), where a variation of over 50 per cent. is the rule. But there are two striking exceptions. The uplands of Alice Springs (32 per cent.) and Camooweal (36 per cent.) form ‘ oases ’ of slightly better territory within the 40 per cent. isopleth. In the map I have joined them, but possibly they are distinct.

Less easily explained is the extremely unfavourable region from Carnarvon to Condon. This culminates in Onslow, which has an average variation of 50 per cent. The average annual rainfall is 8·42 inches, and for 31 years (1886–1916) the record (in nearest inches) is as follows :

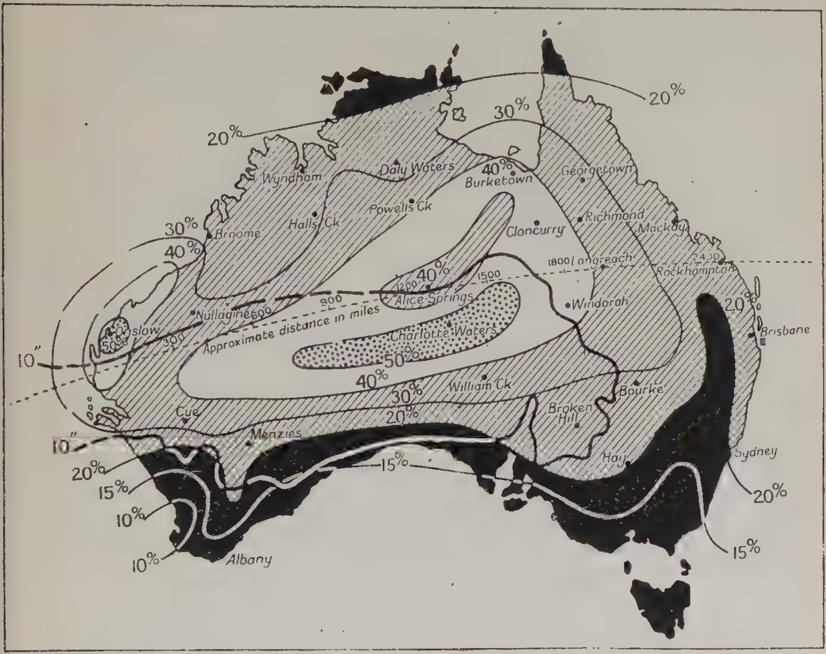


FIG. 125. Rain reliability isopleths for Australia. The figures show the percentage average variations from the normal annual rainfall (1891–1910). The black areas have the most reliable and the dotted areas the least reliable rainfall.

THE ERRATIC RAINFALL AT ONSLOW, WEST AUSTRALIA

1886–90	2,	8,	14,	19,	11
1891–5	3,	6,	11,	3,	6
1896–1900	1,	11,	4,	6,	27
1901–5	3,	4,	6,	16,	5
1906–10	7,	9,	10,	27,	7
1911–15	5,	1,	7,	2,	10
1916	15				

The lowest was 57 points in 1912, and the highest 26·96 inches in 1900. The great variation is probably due to the fact that this is really a portion of the trade wind desert, but that occasionally extremely vigorous rainstorms associated with the summer Low (and sometimes accompanied by Willy-Willies) impinge on this coast.

The map does not show any marked improvement south of the Gulf of Carpentaria, such as might be expected from the passage of many Lows down that region.

The 10-inch isohyet is seen to pass through the reliable rain region along the south-west. This is of importance in wheat cultivation, and shows that in the western state a rainfall of 10 inches is of much greater value than in the Riverina. It also indicates that wheat-growing should be a fairly reliable business along the coast far to the east of Albany—although the rainfall is low.

Wet Seasons. This useful map (Fig. 126)—published by Mr. Hunt in 1916—shows the duration of the wet seasons. At Mr. Barkley's suggestion, those months in any district whose rains exceed the geometric mean of the monthly rainfalls are classed as 'wet'. In the northern area all the wet months are in summer, in the south they are all in winter. The intermediate belt (shown by shading) has generally two periods of rainfall, one due to summer influences and the other due to winter influences.

The region and periods of the prevailing coastal storms are also indicated. These are given in the following table, and are described in later sections.

Coastal Storms

North-west coast hurricane (Willy-Willy)	November to April.
North-east coast hurricane	December to April.
Brisbane storms	February to June.
Southerly bursters	October to March.
Cyclonic storms off south-east coast	May to September.
Southern ocean storms	Winter and spring.

Rainfall Uniformity. At first glance one might be inclined to think that this chart should express much the same features as the Rainfall Reliability Map (Fig. 125), but this is not the case. The latter showed us where the rains were likely to agree with the average graph; the present map shows us where the average graph exceeds a datum-line (1 inch) throughout the twelve months. It takes no account of fluctuations but only of averages (see Fig. 127).

The isopleth marked 2 means that for localities along this line there are *two* months in the year receiving over 1 inch of rainfall, and so on for the other figures.

The chief interest is attached to the twelve-months isopleth which bounds the region of greatest uniformity. This is confined almost wholly to the south-east, and lies east of a line from Mitchell (Q.) to Cape Otway (Vic.). The north Queensland coast, except for a few small areas, is not favoured by uniform rains, while the Darling Downs region is particularly fortunate.

The chief bearing of this chart is on the question of vegetation. Many plants require rainfall all through the year, a break of a month or two being deleterious. This applies especially to the tropical or Malay flora which is present along the east coast of Australia.

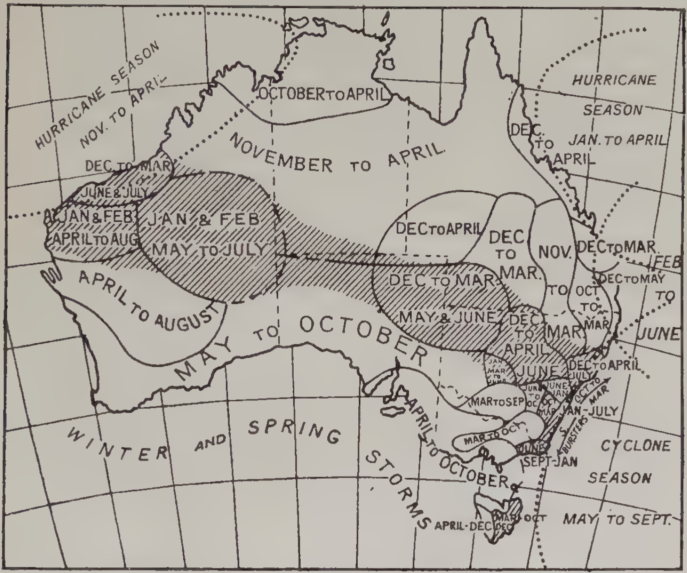


FIG. 126. Duration of wet seasons. The wet periods shown on the map include those months in which the average rainfall exceeds the geometric mean of the monthly rainfalls. The seasons of coastal storms are also shown.

The 12 isopleth does not agree with the boundaries of the thick tropical or temperate rain forest (see next section), so that I was led to plot another feature in the distribution. This consisted in finding which regions had a really considerable rainfall for a good many months of the year. I chose the amount of 2 inches falling during each of seven months in the year. This feature is plotted as the solid black areas, and will be found to agree very closely with the tropical rain forest to the north of Port Macquarie and the temperate rain forest to the south of this latitude. In these black areas, as we have seen, the rainfall practically equals the evaporation (see Fig. 95).

The absence of forests in northern Australia is seen to be associated with the lack of *uniform rain* in that region, though the *totals* amount to very considerable figures.

Rainfall of the World. Australia covers a considerable area, although it is one of the smallest continents. Hence the lessons deduced from its rainfall distribution can be applied to most of the other important regions of the earth.

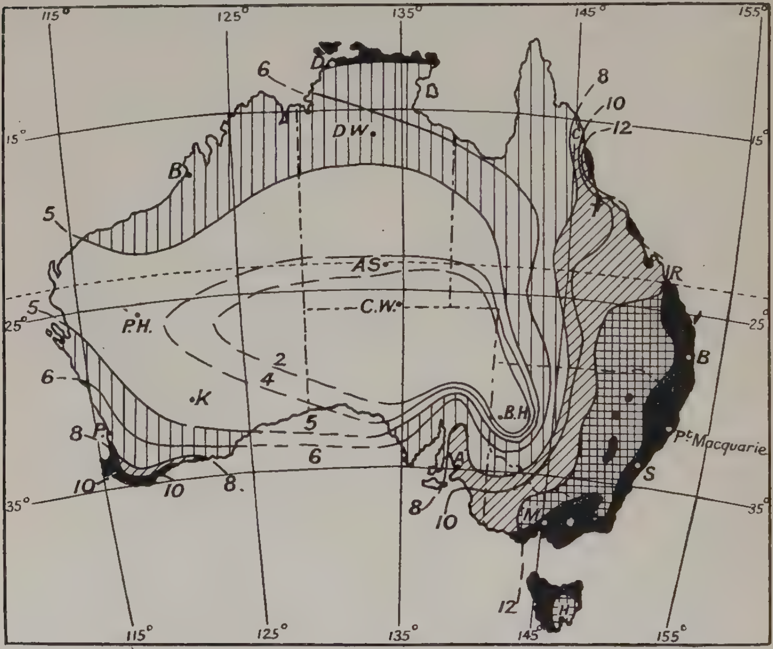
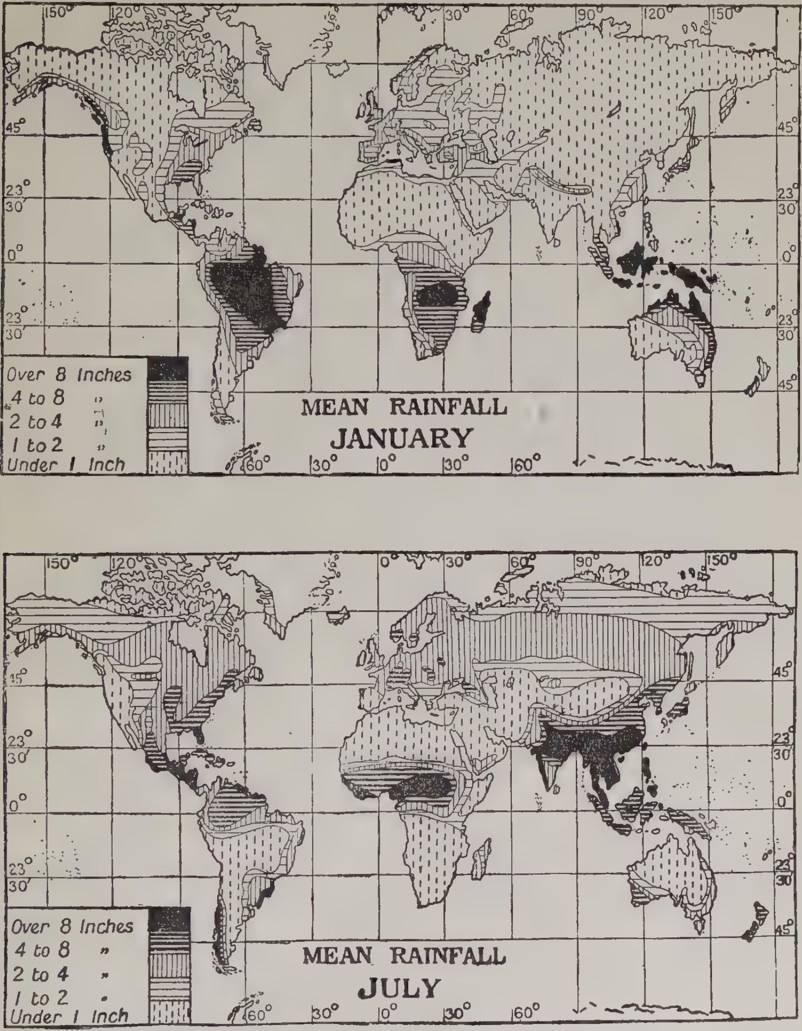


Fig. 127. Rainfall uniformity. Isopleths show number of months receiving over 1 inch of rainfall. Black areas receive 1 inch additional during each of seven months as well as 1 inch in each month of the year.

In January the sun is near its southern limit and a constant succession of low-pressure areas gives heavy rain to the heated north of Australia. The same effect is of course felt in South Africa and in Brazil (see Fig. 128). Here also heavy downpours occur right through the hot months in the belt between the equator and the tropic of Capricorn.

The trade winds and coastal Lows on the north-east coast of Australia extend the rainy region down the Queensland coast. The same conditions obtain near Madagascar and near Rio de Janeiro.



Figs. 128, 129. Mean Rainfall for January and July.

The south-west of Australia is now almost rainless, and so is the west central region of the continent ; and the same features are exhibited in south-west Africa and in South America. Even the Andes, rising to 25,000 feet, are unable to produce rain (by cooling the winds) if the pressure systems are adverse.[1]

The south of New Zealand projects far enough south to still remain in the belt of Antarctic storms (which has moved to the south, swinging with the sun). In the same way southern Chili receives much rain in its summer.

In the northern hemisphere in January it is mid-winter, so that on the whole it is a dry period. The chief rainy regions are in western Europe and in British Columbia, where the constant westerlies associated with the polar side of the high-pressure belt give rains just as they do in Southern Australia. On the east coasts of U.S.A. and in Japan, there are fairly heavy rains because favourable cyclones pass along the coast at times, although the predominant wind direction in winter is naturally westerly (i.e. the offshore monsoon and therefore dry).

All the interior of North America and of 'Eurasia' is dry through the winter. The high-pressure belt is dominating the Sahara, and only its northern fringe in Algeria, &c., receives rain (for exactly the same reason as does 'Swanland'[2] in West Australia in *winter*).

In the southern winter (July), as shown in Fig. 129, Capetown and Chili are affected in the same way as our southern coastlands. Probably coastal Lows move along the east coasts and give some rain to Uruguay and Madagascar, while the south-east trade wind blows about latitude 23° and gives rain also to these east coasts, especially if they be elevated.

The maximum rainfall belt is all north of the equator, the axis of greatest rainfall being about 10° N. latitude. The dry belt (connected with the high-pressure axis) is also displaced to the north, lying near 25° N.

The chief rains of the cold northern temperate regions occur in their summer. We have no similar regions in Australia, and this aspect of the problem need not be discussed in detail.

Rain Making. It is natural that in times of drought people should give much attention to the possibility of producing rain artificially. So much has been accomplished by electrical energy that there is some excuse for the belief that in this form of energy we have an agent whereby clouds may be induced to part with their moisture. Indeed it has long been shown that water vapour will condense under suitable conditions when the air containing it is ionized (by subjecting it to ultra-violet rays, or to an electric discharge, &c.). The atmosphere is indeed in part ionized by emanations from radio-active minerals in the earth's crust.

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[1] Hence high mountains in central Australia would be of little use.

[2] Swanland is the wet south-west of West Australia, W 4 in Fig. 163.

Unfortunately the conditions in the field do not at all resemble those in the laboratory, while it is certain that in the great majority of rainstorms the electrical effects are purely secondary. The rain is due to the cooling of the moist air, and unless we can artificially cool large masses of air we cannot imitate nature's processes.

Let us see what amount of energy is involved in the production of one inch of rain over a square mile. Bates (in his *New Zealand Report* in 1907) writes :

'An inch of rain corresponds to 21,635 gallons to the acre, or 64,640 tons to the square mile. The heat released by the condensation from vapour to water for an inch of rain to the square mile is estimated as equivalent to the work done by 100,000,000 horse-power for half an hour. Consider the total effect of such a rain-wind five hundred miles wide and three miles high, blowing for an hour at the rate of twenty miles.'

We know that such forces are involved in most thunderstorms, and man can never hope to imitate them.

Professor Abbe of the U.S.A. Weather Bureau writes :

'In dry countries the moisture is brought from a great distance—a hundred or a thousand miles—by currents of air that are slowly rising and rolling over and over on themselves. The upper part of the roll makes a cloud, the lower part is clear air.

'Raindrops are formed either slightly, at *night time* when the top of the cloud comes down in the absence of sunshine, or more freely in the *daytime* when the vertical extent of the roll is greatly increased by the sun's heat.

'If in the daytime the overturning extends from sea level upward, then enough moisture is carried up to form a thunderstorm.

'I do not see how man can possibly exert any appreciable influence on the formation of rain. . . . The forces involved in this atmospheric overturning (even in the smallest thunderstorm) are enormous. More energy is involved than is represented by all the steam engines in the world.

'The best that can be done is to save the water that falls in wet regions, and use it to irrigate in dry.'[1]

It would seem probable, therefore, that the initiation of a tropical thunderstorm is due to an extra amount of overturning due to a specially warm day (when moisture conditions are otherwise favourable). One school of rain-makers believes that the formation of a nucleus of raindrops artificially (by electric discharge or other similar fashion) in a large cloud will, as it were, 'inoculate' the other molecules of water vapour. *Solvitur ambulando.* We do not know that Nature uses this method in her rainstorms, and it is difficult to see how changing the electrical conditions in a few cubic yards of air can bring about the cooling necessary for complete condensation, such as occurs in a thunderstorm.

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[1] Cleveland Abbe, on Rainmaking, *Monthly Weather Review* (U.S.A.), November 1907.

A well-developed thundercloud may be described as one of the largest protuberances on the earth. Nature has here generated a system which dwarfs Mount Everest. The latter is 5 miles high; and its base (assuming a slope of 25°) would be about 315 square miles. The thundercloud is the same height (see Fig. 30), and has a base, according to Milham, of 150 × 40 square miles. This is what the rain-maker must reproduce!

Since our arid regions owe their rain almost entirely to thunderclouds, it does not seem likely that the rain-maker can do much to improve their prospects.

Drought. In more than one-third of Australia drought is a permanent condition, while exactly one-half of Australia receives practically no rain for six months of the year. It is, however, in the borderlands between these arid regions and the well-watered districts where King Drought is most feared. For here grows our main wheat crop. and here are situated our chief stock regions.

As regards the inland portion of South Australia, Victoria and New South Wales, very dry conditions or true droughts have occurred about once every three years. Quayle cites the following (since 1880) in *Climate and Weather*: 1881, 1884, 1885, *1888*, 1895, 1896, 1897, 1899, *1902*, 1907, and 1911. We may add the disastrous years of *1914* and 1919. Of these 1885 was bad only in South Australia, and 1911 had good rains in the least useful season (summer)

There are two main types of drought years, shown especially well in 1888 and 1902.

Type.	*Other Years.*	*Pressure.*	*Highs.*	*Lows.*	*Remarks.*
A. *Like* 1888	1895 1907 (1914) 1919	Much above normal.	Strongly developed, somewhat Northern tracks, and no digressions.	Antarctics on normal tracks, but no tropical cyclones.	General lack of humidity.
B. Like 1902	1896 1897 1899 1911 1914	Much above normal.	Often located over S.E. Australia for long intervals.	Intense Lows often located over Tasman Sea. Feeble over Australia.	Rain storms deflected too far South.

CHAPTER XVII

THE HIGHS AND LOWS

In the second chapter some of the chief features of the Highs anticyclones) and Lows (cyclones) were described as far as they appeared on the daily weather map.

We may repeat their salient features in the following table—which refers to the southern hemisphere only, and especially to the southern half of Australia.

	High or Anticyclone.	*Low or Cyclone.*
Vertical Circulation.	Mostly warm descending air.	Mostly cool ascending air.
Horizontal Circulation.	Counter-clockwise; and at the surface, very obliquely away from the centre.	Clockwise; and at the surface, very obliquely into the centre.
Isobars.	From 29·9 inches up to 30·7 inches.	From 29·9 inches down to 28·0 inches.
Centre.	Usually about 30·2 inches.	Usually about 29·6 inches.
Shape.	Usually an oval with long axis east-west. (See Fig. 87.)	Irregular—may be an oval with long axis north-south.
Extent.	About 1,500 miles wide, but often equal to Australia in area.	Much smaller over the land; but usually indeterminate, as over the ocean.
Winds.	Low velocity. Calm in centre. In front south and south-west winds. In rear north winds.	High velocity, steeper gradient. In front north winds. In rear south-west or south winds.
Temperature.	Cool in front. Hot in rear in summer. Cold in rear in winter.	Converse of High.
Rain.	Rare except on the coast, when onshore wind.	Usual, owing to the cooling of the moist ascending air.

The spiral outflow (High) or inflow (Low) is a feature which was strongly insisted on in the past. But it seems clear that this is a surface feature only, and practically vanishes at a thousand feet up. When we realize that both these eddies probably often extend up to the stratosphere (i.e. 30,000 feet up), it is obvious that this spiral movement is not a very important character. The theory is approximately as follows.[1]

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[1] The theory involved in this delicate balancing of the forces acting on an air current is discussed in Shaw's *Forecasting* (page 43), to which the reader is referred.

The rotation of the eddy is due to the combined effect of two major forces—the pressure gradient and Ferrel's law. The former tends to move the air from areas of high to areas of low pressure, *directly across the isobars*. The Ferrel effect (due to the rotation of the earth) tends to make the air blow *parallel to the isobars around* the centre of pressure.

At the earth's surface, the turbulence of the air (due to friction with obstructions, and to convection) has the effect of greatly diminishing the Ferrel effect. Here, therefore, the pressure gradient dominates slightly, and so the winds deviate from the isobars.

But in the free air (above 1,000 feet) the dynamic rotation is more important, and when the air is in steady circulation, it is found to flow round the isobars, and the 'spiral' effect is not in evidence.

Paths and Velocities of the Highs

Since the centres of the Highs lie usually either on the mainland or very near to it, it is possible to plot them fairly accurately—much more so than for the Antarctic Lows.

The average monthly pressure results for many years must of course show fairly well the favourite latitudes of the high-pressure systems. For the *locus* of their centres must determine the central isobar of the average map. If we draw lines, therefore, along the long axis of these central isobars (see Figs. 57–62) we shall get the average positions or axes of the high-pressure centres. These axes are shown in Fig. 68.

Some Highs depart considerably from these averages axes; but speaking generally they are much more regular than are the Lows. On 27 June, 1910, the axis lay over Cooktown (see Fig. 130), which is unusually far north. At this period it usually passes through Brisbane.

In the following table I give the positions for the various months in 1913. Here also are given the average velocities (to the east) in each month. The subject has only lately been investigated in detail, and so these figures are probably not typical—for at least twenty years would be required to get the normal velocities.

Position and Velocity of Highs in 1913

Month, 1913.	*No. of Highs.*	*Latitude while crossing*			*Mean Latitude.*	*Limiting Latitudes.*	*Mean Velocity, 24 hrs.*	*Extreme Velocities, 24 hrs.*
		Longitude 115° *E.* (*Perth*).	*Longitude* 135° *E.* (*Alice Springs*).	*Longitude* 155° *E.* (*Brisbane*).				
Jan.	5	35° S.	37	37	37	34–38	500	210–800
Feb.	4	34	38	38	37	33–40	590	240–1,200
March	5	34	35	36	34	28–38	428	260–700
April	4	33	38	40	37	31–42	487	300–800
May	5	34	34	36	35	32–43	392	160–960
June	4	30	30	44	33	27–46	275	100–500
July	5	34	31	33	33	25–37	424	270–600
Aug.	6	29	30	34	31	25–44	596	400–800
Sept.	5	31	31	33	32	27–44	560	250–800
Oct.	6	34	37	35	35	30–40	770	500–1,000
Nov.	7	36	35	29	33	20–39	650	350–900
Dec.	5	35	37	36	36	33–40	590	330–800

In the year 1913 the Highs moved (to the east) in lower latitudes in summer than in winter, as we should expect. The most southern track was along 37° in midsummer, and the most northern track along 31° in midwinter. The character of the fluctuations can be seen from the column headed 'Limiting Latitudes'.

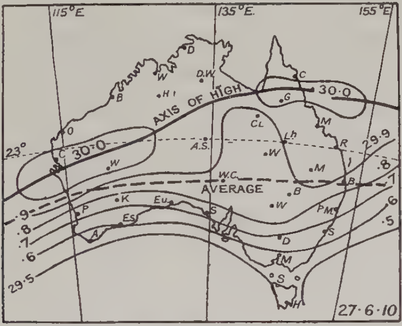

Fig. 130. The axis of the High lying unusually far north. The average for June is shown by the broken line.

The average velocity to the east during this year was 522 miles in each 24 hours. There were about five distinct anticyclones crossing Australia in each month. (See Fig. 87.)

The Tracks of the Low-pressure Systems. In Europe and to a certain extent in the United States there is a strong tendency for the Lows to travel along fairly definite tracks. These are often determined by belts of water—such as the English Channel or the Great Lakes.

In Australia our unbroken land-mass does not furnish similar cool moist belts for the passage of the Lows ; yet certain favourite paths can be determined in Australia. The detailed record of tracks does not cover many years, and the following results are based on four years only. They are therefore approximate.

There are two fairly well-defined low-pressure belts (the tropical and the Antarctic) which have been discussed previously. Their eddies may keep distinct ; but examples of tropicals moving south into the Antarctic track are by no means rare.

The Antarctic Lows are generally centred to the south of our stations, so that the tracks shown are nearly always those of the upper ‘ limb ’ (or margin) of the Low, and not of the actual centre. Hence the regularity of the tracks along our south coast is inevitably exaggerated.[1]

In the tropical area—especially in summer—the centres can be plotted from actual barometer records. The paths are somewhat discordant, but some well-marked features can be made out. There is also a definite seasonal variation.

In the two charts (Figs. 131, 132) are given the relative number of storms which follow along (or near to) the respective tracks.

The record is too short to be quite representative, but it shows that the Antarctic type predominates in the colder months—as we should expect. The tracks were a little farther north in winter also, but the centres cannot be at all accurately charted, for reasons stated.

As regards the tropical Lows, the charts show that their drift is to the south-east everywhere except on the north coast, where they tend to move to the west. These paths are evidently in accord with the drift of the upper air. This feature is discussed in detail in a later chapter.

The chief variation, however, occurs in the north-west of the continent. In the cold months this is almost free from Lows. In the hot months it is a regular ‘ nest ’ of them. They hover over this area as if loth to leave it, and the track of their centres becomes a jumble which can hardly be deciphered. I have indicated this condition by the circles. [The figures therein show the relative periods in which they obtain, as compared with the more definite Lows moving along the tracks shown.]

We may now consider how the tracks differ in the four seasons. For the hot months the conditions are described fairly fully in Chapter XVIII. We find that in addition to the two favoured tracks to the south-east across the continent, there are also tracks off the Queensland coast and less frequently tracks off the north-west coast ; and here the occasional hurricanes develop.

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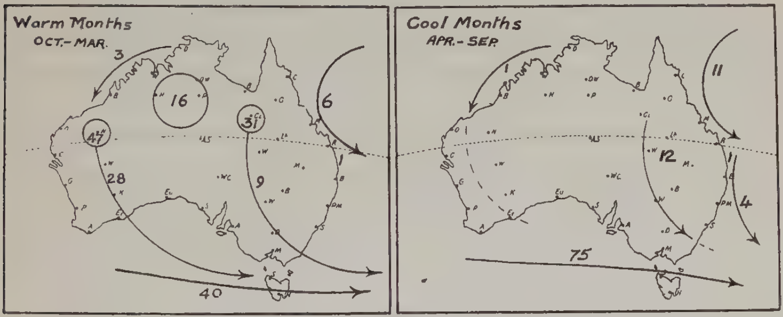
[1] Many of the Antarctic Lows develop considerably north of Antarctica.

In autumn the land is still hot and the tropical Lows are more akin to the summer than the winter types. A special feature is the prevalence of Lows passing down the east and south-east coasts. These cause this region to receive its maximum rainfall in autumn.



FIGS. 131, 132. Paths of the Lows in the six warm and the six cool months, with their approximate relative abundance. The circles in Fig. 131 show the 'convection domes' (see Fig. 135). The tropicals moving to the south-east merge with the Antarctics. (Based on four years only.)

In winter the tropical Lows are relatively unimportant. They keep to the eastern half of the continent ; though one or two may appear off Onslow and move to the south-east.

In spring conditions do not differ greatly from those obtaining in winter.

THE STRUCTURE OF THE HIGHS AND LOWS. We must always remember that meteorological phenomena are more complex close to the surface of the earth than at any other level. Here the uneven surface of the earth gives rise to friction and to obstruction eddies; while the uneven heating of the various areas of rock, vegetation, water, &c., gives rise to convection currents and to eddies due to heat.

Hence we must be careful not to use a definition of a large eddy which will only describe its lowest layer. Thus we describe a High somewhat differently nowadays (when upper air research has taught us much about its structure) from what was considered correct twenty years ago.

The old general theory of atmospheric circulation relied perhaps too much on temperature distribution *at the earth's surface*. The newer theories give more and more importance to dynamic effects involving the whole atmosphere up to a height of at least 10 kilometres. Meteorological theory is in a state of flux; indeed, one of our chief authorities stated recently, 'It must be confessed that the circulation of the atmosphere, the basis on which all meteorology depends, remains more or less a hopeless puzzle.'[1]

It is, however, not difficult to show what is the trend of modern investigations. A High was formerly supposed to be a descending mass of cold air which produced a surface circulation whose winds blew spirally outwards. It is now known that the air in a High is in general warmer than is the surrounding air, and it is only at the surface that there is any important *outflow*. A few hundred feet above the surface the winds blow round the centre of high pressure along the isobars.

The Low in the same way differs throughout the greater part of its structure from its condition at the surface. It is usually composed of cooler air than that surrounding it, and its winds blow along the isobars, except at the surface, where they tend to blow *into* the centre of low pressure.

DINES'S THEORY OF HIGHS AND LOWS. Dines gives the following results as average figures in Britain for the temperature in the two types of eddy in the layer between 1 kilometre and 14 kilometres.

	Height.					
Kilo.	*Miles.*	*Feet.*	*Cyclone* (29·2 *inches*).		*Anticyclone* (30·3 *inches*).	
1	0·62	3,300	+37° F.		+43° F.	
3	1·87	9,900	+14° F.		+28° F.	
5	3·11	16,400	−11° F.		+ 7° F.	
7	4·35	23,000	−38° F.		−17° F.	
9	5·59	29,500	−53° F.	Isothermal	−44° F.	
11	6·84	36,100	−56° F.		−63° F.	
13	8·08	42,700	−54° F.		−72° F.	Isothermal
14	8·71	46,000	−56° F.		−72° F.	

Nearly three-quarters of the atmosphere lies below 10 kilometres, and in the cyclone this layer has a temperature some 18° F. colder than in the anticyclone.[2]

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[1] W. H. Dines, F.R.S., 'Circulation of the Atmosphere', U.S.A. *Weather Review*, November 1915.

[2] Dines, *Cyclones and Anticyclones*, 1914, Scottish Meteorological Society.

It will be noticed that at about 8·7 kilometres the temperature becomes constant in the cyclone, and at about 12·3 kilometres it becomes constant in the anticyclone (see Fig. 133). This layer of constant temperature is the isothermal layer of Teisserenc de Bort, and it approximately bounds the shell of atmosphere with notable water contents—in fact, it lies near the outer cloud layer.

In the cyclone this isothermal layer seems to bulge down into the troposphere (or lower atmosphere) and is much warmer than in the anticyclone—where the layer is found 4 kilometres higher and is 34° F. colder.

Dines believes that the cyclone is a region where the air is being sucked upwards—for this explains its coldness (by expansion). The operating 'agent' seems to be situated about 10 kilometres above the earth, where the winds are stronger than in any other layer of the atmosphere.

While the details are quite obscure, it can be mathematically shown that there is a very close relation between the pressure at 9 kilometres and conditions in the atmospheric shell below that level. Thus between P_9 (pressure at 9 kilometres) and the temperature of the whole column of air there is a correlation coefficient of 90 (where 100 is the maximum).[1] The correlation with the height of the isothermal layer is about 80. Between P_9 and the surface pressure the correlation is about 65.

Let us for a moment ignore the initial stages in the formation of such a Low. Suppose it has been formed in this layer of the strongest winds (i.e. at 9 kilometres); then a swirl may be set up, much as is produced by withdrawing the plug in a hand-basin. A strong eddy like this has special dynamic properties, and it can readily be understood that it exerts a great influence on the atmosphere in the vicinity. It may in effect draw up air from below, and then sweep it away to the sides below the resistant but elastic roof formed by the stratosphere (see Fig. 133). Thence the air descends to lower levels along much more diffused paths. This latter air is warmed by the compression, and indeed the regions of high pressure (which we know as the anticyclones) probably originate in this fashion.

(This problem is treated more fully in the following chapter.)

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[1] My statement of the correlation coefficients is only approximate. For instance, Dines states that the correlation coefficient between the closeness of the isobars and wind strength is about 0·70 (or, as expressed above, 70 out of 100). See 'Local Circulation of Atmosphere', W. H. Dines, 1916, *Monthly Weather Review*, U.S.A.

CHAPTER XVIII

THE ORIGIN OF THE TROPICAL LOWS IN AUSTRALIA[1]

In the general circulation of the atmosphere the normal state of the air is determined by several independent factors. The interchange of air between the equator and the poles is a thermal system. The building up of belts of low and high pressure at the boundaries of the temperate zone is largely, though not wholly, a dynamical system.

If, however, there were no variation in the surface of the globe—if it were all open sea or level uniform land surface, then it is difficult to see how eddies could arise in these belts. It is the third great factor—the convection due to the distribution of hot and cold areas of the surface—which is probably largely responsible for the splitting up of the belts into a series of rotating whirls of air.

At first it was suggested that it was actually the presence of mountain barriers across the track of the winds which produced these eddies. In the following notes it is suggested that they are associated with and probably due to atmospheric barriers of infinitely greater size which partially obstruct the upper windstreams.

Dines and others (as we have seen) have shown that the ordinary Low of the *temperate* regions cannot be regarded as an area of warm ascending air,[2] for it is considerably cooler than adjoining layers of air (Fig. 133). It is therefore not ascending because it is warm, but on the contrary it is probably cooling because it is sucked up by a high-level eddy (initiated at the 9-kilometre level) into regions of less pressure. The air therefore expands and is cooled, as the *ballons sondes* have recorded.

Dines shows that it is a swirl in the zone of greatest wind velocity which acts as the engine to draw the surface air upwards

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[1] Since some sections in the chapter are somewhat speculative it may be omitted by the junior student.

[2] *Monthly Weather Review*, Washington, April 1916.

(Fig. 133). This swirl probably also draws the stratosphere downwards and so makes the latter relatively warm over a Low. The stratosphere probably descends as a bulge and does not tend to merge into the troposphere. It may be pictured as contained in an elastic envelope which is distorted by external forces, but does not lose its identity.

The difficulty is to account for the initiation of these swirls in the regions of greatest wind velocity. Normally the atmosphere is not at rest but is always *moving*, just as the hydrosphere is always in motion, in the form of broad currents or as tides. It has been well said that it is the *calm* regions which require explanation rather than those where winds are always in evidence. There are grounds for the belief that even in the stratosphere strong winds are quite usual, and Blair states that their velocity amounts to 45 miles per hour.[1] The steady horizontal streams of the stratosphere, however, tend to keep distinct from the turbulent air of the troposphere below.

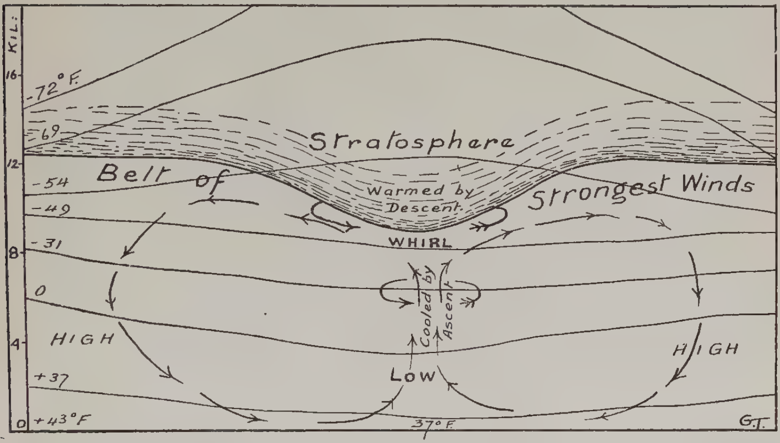

FIG. 133. Vertical section showing the structure of a wandering cyclone in the temperate regions (52° N.). Based on Dines. Average temperatures (Fahrenheit) also inserted.

The Lows are constantly forming in the three major low-pressure belts. In Australia we experience about fifty well-defined Antarctic Lows and about thirty tropical Lows every year; besides some indefinite surges and ephemeral depressions whose life history is not very clear. Hence the agent which initiates these widespread phenomena must be almost as ubiquitous as the Lows themselves.

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[1] Blair, 'Planetary System of Convection', *Monthly Weather Review*, April 1916 (Washington).

Convection. This external factor, which so influences the upper winds at the 9-kilometre level, must be connected either with the stratosphere above, or the troposphere below. Insolation has little *direct* effect on the air, which is heated by reflection and radiation from the earth below. This is shown very clearly by the Eiffel Tower records, where the heat changes are felt at 1,000 feet about one hour later than at the ground. Hence it seems logical to look to the earth as the immediate source of the disturbance rather than to the outer stratosphere layers, which normally have no notable effect.

The agent which best satisfies these conditions is convection (see Chapter IX). It seems probable that the reason why convection has not been credited with its due place in the origin of the Lows is because there seem to be several somewhat distinct phenomena described by the name 'Low'. These are the ordinary depressions, cyclones, or low-pressure areas of the cool temperate regions and the more or less permanent centres of low pressure of other regions.

The eddies of the cool temperate zone have been carefully investigated in the past twenty years, with the results noted previously. It seems probable that somewhat different conditions obtain in the areas affected by the permanent summer low pressures of north-west Australia, of Persia, of Iceland, or the Antarctic (see Fig. 134).

It will be noted that these are all inclement regions, far removed from centres of research, and so the actual atmospheric conditions can only be surmised in most cases, Australian data being perhaps the most complete.

My experience in the air, limited as it has been, is sufficient to convince me that convection is a much more potent factor than has recently been allowed. One has only to leave the ground a few times to find that bumps are by no means confined to still hot days. Even with a wind of 20 miles per hour the convection columns over favourable localities such as stony hills, large towns, &c., are perceptible for several thousand feet. They may be affected by the prevalent drift and lean to leeward, but the rising air preserves its identity in a remarkable fashion. (*Vide* Lieutenant Sleeman's Notes in Chapter XXV.)

Local Convection Columns. Thunderstorms and cumulus clouds are evidence of the power of convection to build up peaks of air in spite of strong horizontal air currents. The former reach up to 30,000 feet quite generally.

With regard to thunderstorms Hann gives the following data:

> In Batavia, Bergsma has noted lightning from a thundercloud which occurred at about 6 kilometres vertically overhead. It is found also that the height of the cloud increases with the height of the land beneath. In Europe the lower surface is usually between 1,000 and 3,000 metres above the sea. In dry hot weather the clouds being due to convection are naturally highest. For the same reason they are common in hot regions and rare in polar regions.
>
> In the *equatorial* zone there are about 100 days with thunderstorms per year, and from 50 to 30 in the *temperate* zone. They are almost absent in the *polar* zone. They proceed over the land at about 40–60 kilometres per hour (25–38 miles per hour).

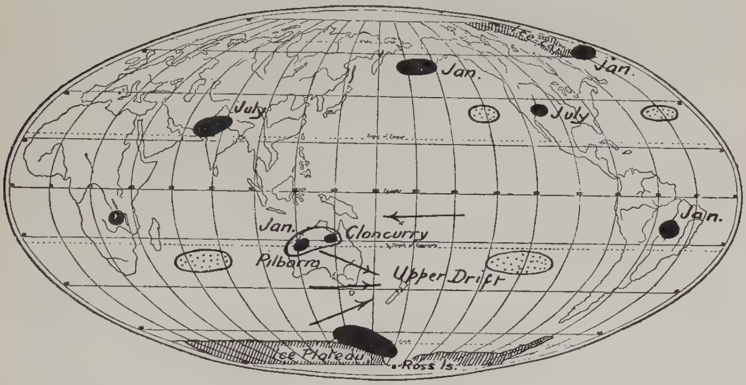

Fig. 134. Centres of convection shown black. The Antarctic and Icelandic 'Domes' are the chief, and lie near the two ice-caps. The Persian is the chief of the less permanent Domes (see p. 177). The dotted areas are the semi-permanent areas of high pressure. The arrows show the upper-air drift. Ice plateaux shaded.

Cumulus clouds are less striking than thunderstorms, but show the effect of convection in no less definite fashion. From Mr. E. T. Quayle's *graphic* record of Melbourne weather, I have taken out the cumulus data for 1915, which is given in the following table.

Cumulus at Melbourne

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*
Days of strong cumulus .	8	1	0	3	1	1
Surface wind . .	S.	N.	—	N.	NW.	—
Speed of latter, miles per hour	10	12	—	6	5	2

	July.	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Days of strong cumulus .	3	4	7	7	3	4
Surface wind . .	NW.	NW.	NW.	Var.	Var.	NW.
Speed of latter, miles per hour	3	9	10	9	10	15

The average surface-wind velocity is here shown to be just over 9 miles per hour. The direction of movement of the cumulus is similar to that of the surface wind, except that the westerly component is stronger.

Fabris' investigations at Rome show that a surface wind of 10 miles per hour is about equivalent to 18 miles per hour at 6,000 feet (see Fig. 179, later), and this is probably about the rate at which the narrow convection columns (which form the cumulus) travel along in accord with the westerly drift in southern Australia.

Quite often a sea-breeze or other surface wind cuts off the convection effect of the cumulus column from its place of origin—the hot ground. But the column still maintains its identity and travels along at the same rate to the east. [The trade wind may cut off convection effects of a far larger type in a similar fashion, as shown in Fig. 152.]

Milham gives the following data for cumulus dimensions :

Top : Mean 6,000 ft. max. 15,000, min. 2,400
Bottom : ,, 4,400 ,, ,, 12,000 ,, 1,600

Hence under favourable conditions the cumulus column extends 15,000 feet from the ground, or half-way to the isothermal layer. It is not too much to expect that the infinitely larger ' Convection Dome ' (which is described later) towers above the whole troposphere, and may indeed bulge the stratosphere up above its mean position for the latitude concerned.

Major Centres of Convection. The favourable condition for strong convection to occur is of course a large, steep, horizontal temperature gradient such as would be shown by the crowding of the isotherms on a map of the locality. It does not matter much what the actual temperatures are, provided the range be considerable. Thus one would expect a strong convection effect from a relatively warm open gulf penetrating the Antarctic ice plateau.

In 1911–12 the writer spent some time in MacMurdo Sound, Antarctica, and experienced the winter blizzards, which were largely due to the strong convection effect. The ice plateau (7,000 feet) and Royal Society Ranges (13,000 feet) were only about 20 miles away to the west, and the Erebus massif (13,000 feet) lay just to the east. The average temperature of our winter quarters in midwinter was −20° F., so that the ice massif at 10,000 feet would have an average temperature of −50° or so. They would thus be 80° colder than the open sea (+28° F.) near by, and the convection effect would be very considerable.[1] Somewhat similar conditions obtain around the Antarctic plateau. On the low-level ice, where Amundsen spent the winter, such storms were noticeably rare. He was 200 miles from the plateau, and so convection was proportionally reduced.

In Persia in summer the temperature is about 90° on the coast and about 80° inland. The 12,000-feet plateau of Thibet is about 40° colder.[1] The Indian Ocean is much about the same temperature as the land, so that the chief convection effect (and the semi-permanent Low) should be between the Himalayas and the Persian Gulf. This is found to be the case.

Off Iceland is the chief remaining semi-permanent Low. It is most strongly developed in winter, for then the gradient between the Gulf Stream and the Greenland plateau is the strongest. Here again the sea water is 28°, and the Greenland plateau (of 6,000 feet) is about 60° colder.[1] (In summer the difference is only about 30° and no well-marked stationary Low is developed.)

THE CONVECTION DOME. Now let us turn to the phenomena in a *fluid* stream. To produce eddies it is only necessary to place an obstruction in the path of the stream. Usually this is a rock or snag; but one could imagine that a well-defined body of water (of different temperature and density), if projected through the stream, would be quite capable of acting like a solid and of producing eddies in the stream. (We know of fresh-water springs rising through the sea and keeping quite distinct, as for instance near Perth in West Australia.)

I imagine that some such action takes place in the atmosphere. Over such centres (of which the chief have been briefly described) there is built up a column or dome of *warm* ascending turbulent air. It will have usually a cyclonic circulation—which will probably be of small intensity, for it will often consist of relatively dry air. It may well be several hundred miles across and rise to 25,000 or 30,000 feet. It may at times be dissipated, and may fluctuate under the influence of the strong winds of the upper troposphere. I believe that it will have individuality enough to hinder the free passage of the upper winds, and to suffice to initiate the low-pressure systems (see Fig. 152 A).

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[1] Other factors such as Radiation and Gravity Flow come in also. The whole question is still little understood.

Observations at Washington D.C. in July 1917 on the formation of subsidiary 'scarf' clouds corroborate this view. Thus Dr. C. F. Brooks writes: 'The great cumulus cloud, like a mountain, interrupts the free flow of the wind. Perhaps these scarf clouds are formed by the winds rising to pass over the dome (i.e. cumulus), rather than by the up-push of the rising cloud columns.' (*Review* No. 624.)

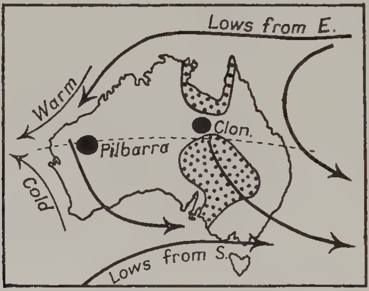


FIG. 135. The favourite paths of the Lows in Australia. The two convection centres are shown black. The ocean currents in the west are given. The central lowlands are dotted.

Moreover, there are strong indications that the building-up of this 'dome' increases day by day, until it becomes as it were top-heavy. Thereupon an eddy of air 'buds' off—much as the satellites leave the parent—and sails away in the current of the upper-air drift, which is usually to the east.

CONVECTION DOMES IN AUSTRALIA. I am not able to discuss what occurs elsewhere, but in North Australia we have two localities in which in summer such convection domes seem to be built up (Fig. 135).

Our hottest region in summer is the Pilbarra district, which has average temperatures of 90° in each of the three months December, January, and February. The cool West Australian current flows up the Perth coast and comes very close to Pilbarra. It supplies much of the colder air which forces up the heated air of the hinterland.

The horizontal temperature gradient is much less than in other convection domes which I have noted.

To the south of the Gulf of Carpentaria is another region of less importance. This surrounds Cloncurry, which has a summer temperature of about 87°. The waters of the Gulf are not cool enough to bring about much temperature difference, and we find that the Cloncurry ‘ Dome ’ is much less striking than that of Pilbarra (Fig. 135).

These heated areas are closely connected with the life-history of our summer monsoon. The early description of the monsoon as *steady uniform* streams of air is not borne out in our monsoon area. A tremendous increase in the number of tropical Lows occurs, and they hover for days about the two areas, Pilbarra and Cloncurry, or less often between the two. The chief rains are associated with the ‘ satellite ’ Lows which bud off and move to the south-east. The indefinite broad low-pressure ‘ dome ’ is usually not associated with rain. This is quite in accord with the distinction I suggested earlier in this chapter.

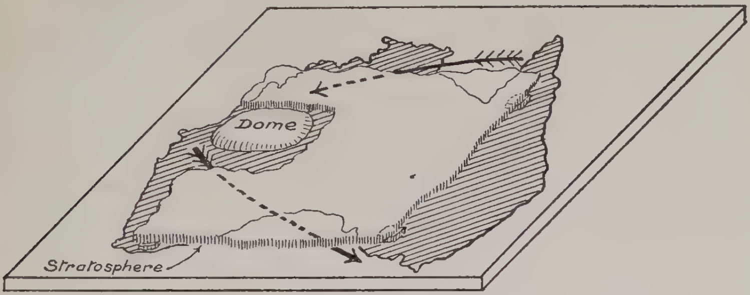
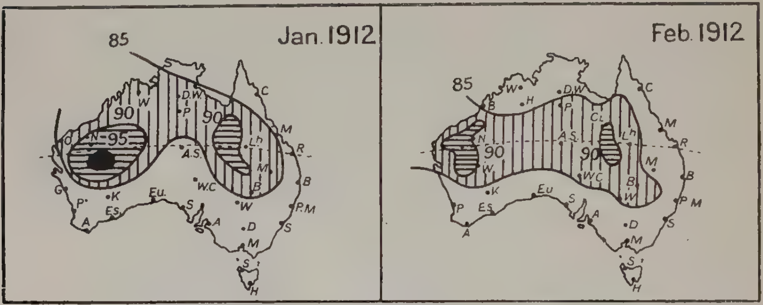


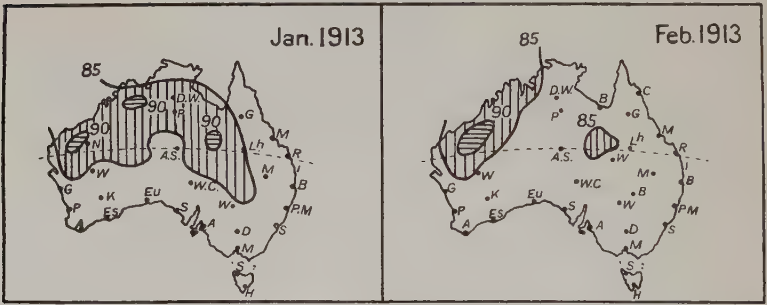
FIG. 136. Diagram illustrating the shallow troposphere stream impeded by a permanent ‘ convection dome ’ in the north-west of Australia. The stratosphere, shown as a broken white layer, acts as a fairly definite ceiling about six miles over the land. The heavy arrows show the drift of the bulk of the air in the troposphere.

We shall obtain a clearer mental picture of the conditions if we consider the actual dimensions of these convection domes (Fig. 136). The Pilbarra dome is probably fifty times as wide as it is high. Thus the height is less than 10 miles, while the diameter is about 500 miles. For an analogy to scale we may compare Australia to a table about 8 feet across. On this stands a small tray about 2 feet across and $\frac{1}{2}$ inch high, which represents the ‘convection dome’. A sheet of glass parallel to (and $\frac{1}{2}$ inch above) the table represents the stratosphere (Fig. 136).

In the earlier paragraphs I have, I hope, proved how stable is even a small convection column. The effect of the colossal column (or dome)—which forms a permanent Low—upon the thin layer of drifting air which we call the troposphere must surely be considerable.



FIGS. 137, 138. Mean temperatures in January and February 1912, showing well-developed convection centres.



FIGS. 139, 140. Mean temperatures in January and February 1913, showing less strongly developed convection centres.

Upper-air data is entirely wanting in tropical Australia except for infrequent and very scattered records of cirrus drift. But the isobars, isotherms, and isohyets of the surface air support the present hypothesis of the effect of the convection dome; as I shall now proceed to show.

CONVECTION AND ISOBARS IN AUSTRALIA. Let us now examine the relation of pressure to temperature in Australia in summer. There is here a pair of convection ‘domes’ which can readily be studied on our weather charts. The results are not complicated unduly by the topographic factor, for from the meteorological point of view tropical Australia is almost a uniform plain, under 1,500 feet (Figs. 137–40).

We find that the convection effect begins about October. The isotherms and isobars thereafter both exhibit similar average features—a double loop projecting south-west and south-east, with the centres near Pilbarra, West Australia, and Cloncurry, Queensland. The tropical isobars can be divided into three broad types—Loops, Troughs, and Central Lows. These may be subdivided as follows:

1. Single loop at Pilbarra (Fig. 145).
2. Trough to south-east from Pilbarra (Fig. 146).
3. Large central Low in which 1 and 4 merge (Fig. 148).
4. Single loop at Cloncurry (Fig. 141).
5. Trough to south-east from 4 (Fig. 142).

There are also two characteristic but rather rare types.

6. Tropical Low curving round north-west coast (Fig. 149).
7. Tropical Low curving round Coral Sea, Queensland (Fig. 141).

These are illustrated in the annexed figures (141 to 147), where a week's changes are illustrated.

We shall find that a general history of our summer pressure controls is somewhat as follows. Early in October the two centres quoted reach a temperature of 80°, the isotherms bending far south to reach these positions. Isobaric bulges to the south-east occur independently at first from both centres, but then one (usually Pilbarra) dominates (Fig. 137), and a trough develops running from the tropics to the southern ocean. This seems to relieve the pressure, and the trough (keeping its identity) moves slowly across Australia to the east (Figs. 146, 147). Often an Antarctic Low either develops at its southern end, or has advanced from the southern low-pressure belt to that favourable spot (Fig. 147). The pressure control in the north usually remains somewhat indefinite for some days, while the convection domes are building up again. Then perhaps the other (Cloncurry) bulge will form, push to south-east, and go through the same procedure (Figs. 141–3).

Some weeks later the double-bulge type of isobars (Fig. 148) comes much into evidence, but the single loops still occur nearly

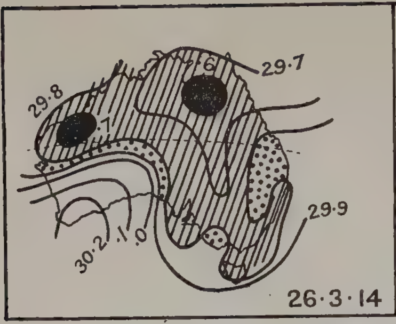


Fig. 141. The two convection domes strongly built up. A loop and trough have developed from the eastern (Cloncurry) dome. (Illustrating type 4.)

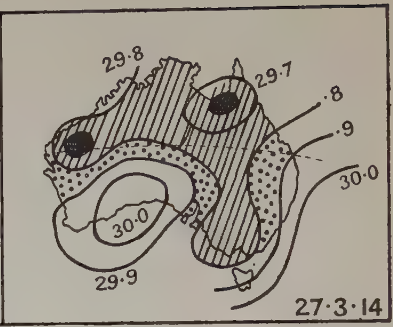


Fig. 142. The conditions much the same, but indications of a satellite cyclone appear in the south-east. (Illustrating type 5.)

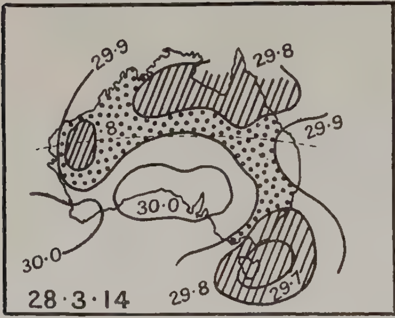


Fig. 143. The south-east cyclone has budded off, and moves away independently to the east.

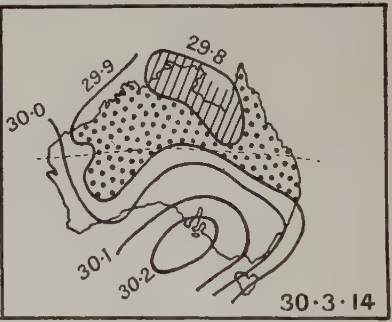


Fig. 144. In two days the Pilbarra dome has diminished considerably, though its effect is shown by the loop in the 29·9 isobar. The Cloncurry dome is spreading across towards Pilbarra.

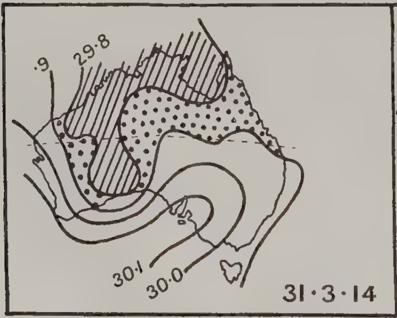


Fig. 145. The Pilbarra dome is intensifying at the expense of the Cloncurry centre. A loop is forming south of Pilbarra. (Illustrating type 1.)

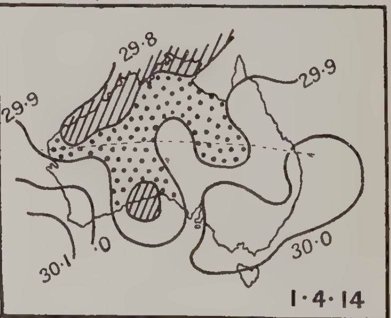


Fig. 146. A trough and cyclone are forming south of Pilbarra (Illustrating type 2 fairly well.)

as frequently. At times, in addition to the trough forming, a satellite eddy moves from the convection dome to the south-east (Figs. 142, 143).[1] The rains are always more abundant when this occurs. Obviously the up-draught and cooling postulated by Dines is more pronounced here in the higher latitudes where the rotation effect has been more strongly developed.

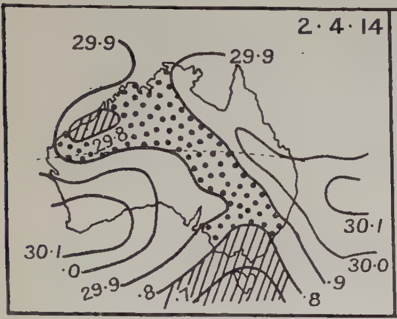


Fig. 147. The southern Low has merged with an Antarctic and is passing to the east; and the process is commencing again.

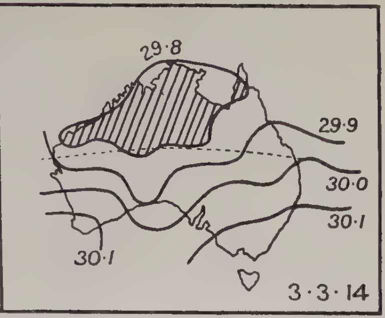


Fig. 148. The merging of the two centres, which occasionally marks the interval between two cycles of pressure development. (Illustrating type 3.)

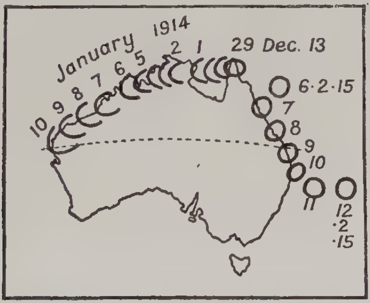


Fig. 149. Examples of the Queensland coastal (type 7) and of the West Australian coastal (type 6). Both slightly generalized. (Figures are dates.)

The chief variations occur when an external cyclone advances from the north-east. It comes steadily along, apparently moved by the upper easterly equatorial drift. Probably some go sailing along well to the north of Australia, but those which enter our waters almost always follow one of two tracks (Fig. 149). They curve round the north-west (type 6) or around the Coral Seas off Queensland. They are wanderers from other convection centres in

[1] In Bulletin 10 (page 27) on Cirrus Directions and Storms, Mr. Quayle briefly discusses the origin of the temperate Lows of Australia.

most cases, in my opinion. But in certain cases the convection dome forms farther north—near Darwin, or in the other promontory—that of Cape York. Here the eddy, when budded off, will be drifted to the west, instead of to the south-east (as it would be if originating on the tropic).

These special Lows (from which our hurricanes or Willy Willies usually evolve) keep to definite paths along the hot coast; because here, I take it, they have the conditions of heat and moisture necessary for their maintenance. When they curve to the south-east into the dry interior of West Australia (e.g. near Onslow) under the influence of Ferrel's law, and of the upper westerly drift (Fig. 135), they proceed as normal cyclones, as has been described previously. On the other hand the Queensland variety on curving to the south-east still move over water, and so may produce a hurricane in the south-western islands of the Pacific.

QUANTITATIVE STUDY OF CYCLONIC ISOBARS IN THE AUSTRALIAN TROPICS. In the following table I show the number of days during three summers on which these types dominated the regions concerned.

GENERALIZED HISTORY OF PRESSURE CONTROLS DURING THREE SUMMERS, 1911–12, 1913–14, and 1914–15.

(Figures give number of days affected by type.)

Type	1.	2.	3.	4.	5.	6.
Date.	*Pilbarra loop.*	*Pilbarra Trough to SE. (moving to E.).*	*Large Low merging 1 and 4.*	*Clon-curry loop.*	*Cloncurry Trough to SE. (moving to E.).*	*Cyclone buds off.*
1911 Oct.	12	12	3	10	1	3
Nov.	18	8	6	12	—	—
Dec.	11	20	7	5	3	5
1912 Jan.	10	7	2	16	2	15
Feb.	23	11	1	18	3	1
March	15	13	1	12	2	1
1913 Oct.	6	13	7	3	—	—
Nov.	13	15	4	3	3	3
Dec.	19	1	12	1	4	—
1914 Jan.	7	7	10	12	1	—
Feb.	16	4	4	15	4	—
March	16	14	11	8	5	1
Oct.	17	2	2	6	7	1
Nov.	12	10	4	7	1	3
Dec.	13	2	8	12	7	3
1915 Jan.	12	3	2	10	7	—
Feb.	20	4	2	6	1	—
March	7	13	3	13	1	—
Total days	257	156	89	171	49	21
Per cent.	47	28	16	31	9	4

The above table shows that on 47 per cent. of summer days there is a loop over the Pilbarra region and on 31 per cent. of the days a loop over Cloncurry region. (These two percentages often refer to the same date, of course.) Loops merge into troughs, which gradually pass to the eastward, on 28 per cent. of the days from Pilbarra loops, and on 9 per cent. from Cloncurry loops. These may fairly be added to the days of their respective loop-origins.

Hence we find that tropical weather is controlled by loops or troughs originating near Pilbarra in 75 per cent. of the warm months—October to March; and by similar pressures around Cloncurry in 40 per cent.

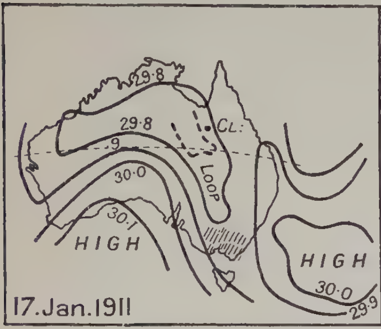


FIG. 150. Cloncurry loop with rain at the tip. Indicating cyclonic action in the upper air near Victoria. (Dashes indicate rain.) The front of the loop on the previous day shown by broken line near Cloncurry (CL.).

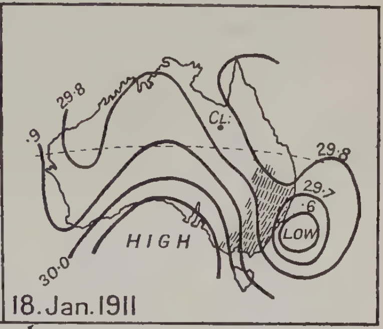


FIG. 151. The tropical cyclone becoming evident in surface isobars. It has probably moved slightly to the east in the last 24 hours.

About 16 per cent. (or 64 per cent. of the remaining period) is characterized by a combined loop or Low situated between the two more typical regions.

The West Australian coastals (type 6) appeared in March 1912, end of December 1913, and in February 1914, i.e. on about 6 per cent. of the days.

Queensland coastals (type 7) were strongly in evidence in January 1912 and also in December 1914 and February 1915, i.e. on about 3 per cent. of the eighteen·months considered.

DRIFTING UPPER-AIR CYCLONES. One fairly common condition in our tropical isobars is illustrated in Figs. 150, 151. Here the tropical loop is moving to the south-east, apparently following rain which has fallen at its tip. Next day a tropical cyclone develops (at the surface) close to the tip, as on 18 January, 1911. It seems logical to assume that the rain of the 17th fell as the result of a cyclonic up-draught in the upper air, whose isobars were only represented by an open loop in the surface isobars. Various stages of this sequence are quite common in other seasons and indicate that high-level eddies often cross Australia, though they probably originate much farther north in the colder months (see B in Fig. 152).

MECHANISM OF THE LOWS. In Fig. 152 I show in a generalized fashion what I believe to be the mechanism of many of our tropical Lows in summer. The sun is heating northern Australia and a convection dome is built up,[1] reaching into the westerly or north-westerly drift as shown. This causes the formation of eddies from time to time in the upper air which sail away to the south-east. They do not always extend down to the surface, possibly being at times obstructed by the trade wind belt.

If conditions are favourable they may supply rain with loop isobars at the surface (see Fig. 150). They may increase in intensity and form a definite cyclonic Low as in Fig. 151.

If an Antarctic Low is moving to the north-east near Australia (under the influence of the dominant drift over the southern ocean) then the two cyclonic eddies merge, readily overcome adverse conditions, and move along the resultant path (near latitude 42° S.) directly to the east. This track has been shown to be the most usual of all the various rain types in Australian weather charts.

SUMMARY

The distribution of permanent winds, of cyclones, anticyclones, and calms is always in a state of flux. Nature makes a compromise from day to day between the various dynamic and thermal controls. The writer believes that the regions of greatest convection (the 'convection domes') are logically more likely to control the supply of Lows and of rainfall and storms than the so-called 'centres of action' (permanent Highs). The latter are the stagnant portions of the atmosphere—the Sargasso Seas of the ocean of air. Here are those regions where convection is least operative, and which nature accordingly uses as her 'Sinks'. They too may, however, act as more or less stable obstacles in the belts of high pressure.

It is easy to trace the 'budding-off' of Highs from the centre of action in the North Atlantic. Every few days an independent anticyclone appears to split away and travel across to France or Spain. It can sometimes apparently be traced around the world—merging in the other centres of action as it arrives in their domain, and then travelling on again.

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[1] Owing to the exaggerated vertical scale of Fig. 152 the 'dome' appears like a cone. It is of course more of a rounded disk (see Fig. 136).

To sum up, I feel sure that until the semi-permanent Highs and Lows are explored at least as fully as has been the case with the travelling eddies of temperate climes, it will be unwise to neglect convection as a very vital factor in our world circulation.

In sub-tropical countries such as Australia the Lows move in three definite directions. Along the *north coast* they move usually to the west as if generated somewhere to the north-east (but south of the equator). They are obviously swept along in the drift of the upper equatorial current, and if near latitude 20° S. often curve round when they reach the ' dome ' over Australia.

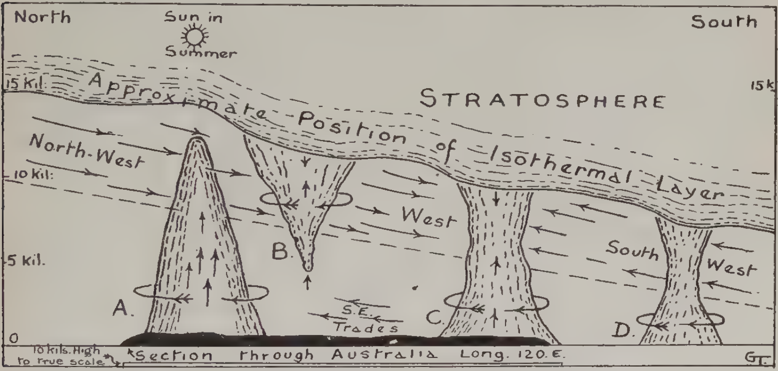

FIG. 152. Generalized diagram (vertical section along 120° E. long.) illustrating the formation of eddies in the upper air of North Australia.
A is a convection dome (at Pilbarra) building up under the midsummer sun.
B is a young tropical Low formed in the north-westerly drift by the action of the convection dome. It may only affect the surface isobars as a loop, but may give good rains owing to the updraught.
D is an Antarctic Low coming from the south-west, and formed of relatively dense air.
C The tropical and Antarctic Lows have fused to form a strong rain-producing Low. It moves along in the westerly drift.
N.B. The vertical scale is exaggerated sixty times. The true scale is indicated at the foot of the diagram.

In the *central belt* of our continent they originate near and move from Pilbarra or from Cloncurry (or thereabouts) to the east and south-east. They are drifted with the upper westerlies.

In the *southern belt* they are mostly beyond our ken, and surge up from the Antarctic with a strong tendency to the east. I imagine that their breeding-ground is on the edge of the great Antarctic plateau.

It would be foolish to suggest that this hypothesis accounts for all cases. Certain difficulties will soon occur to meteorologists if an attempt be made to apply it too generally. For instance, in winter, when no convection domes form over Australia, we get occasional tropical troughs which may cause heavy rain. In June 1912 two such storms appeared first as bulges near Cloncurry. Each of these protruded into a large winter anticyclone, which, as usual, covered most of Australia. One is tempted to suggest that they originated far to the north and had an evolution somewhat similar to those described earlier. But this is at present only speculation.

The fact that no adequate cause has been postulated for those of our Lows which have formed outside Australia is hardly a logical argument against this attempt to demonstrate a very definite cause for the 80 per cent. of our summer tropical Lows, which I believe to be indigenous.

The 'convection dome' hypothesis—as I may term it—assumes that a fluid flowing around an obstacle may produce eddies. It has been shown that a definite obstacle (the 'convection dome') is built up in our troposphere, and that most of the tropical eddies in Australia originate there. The clear skies often associated with the 'dome' show that it is not constituted quite like temperate Lows. The isobars and isohyets strongly support the hypothesis.[1]

One may illustrate the special difficulties of the meteorologist in this very very fundamental problem by the following parable.

Let us imagine a polyp anchored to the bed of a river, on whom has descended the divine fire of research. It is closely affected by the turbulent currents among the boulders. It may realize the moving river above, it may see eddies sweep along in the current. But it can have no conception of the origin of such eddies in some rock far up the river, while the relation of the river to rain or snowfield is far beyond its ken.

Meteorologists are the most unfortunate of scientists. They are confined to the lowest, most complex and turbulent layer of the realm which they wish to explore. The 'prime movers' of the atmospheric system are situated far from the haunts of men, in the centres of vast oceans, in regions of torrid heat or near icy lands, and only the more mobile storms move across to the lands of close white settlement.

In the *ballon sonde*, and especially in the economic development of aviation (which must vastly increase the interest in our science) lies the hope of theoretical meteorology.

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[1] There being no probability of local research in the Australian tropics, the hypothesis is submitted in what is necessarily a somewhat incomplete form. I have to thank Professor Marvin and Mr. E. T. Quayle for their helpful criticism of several points in this chapter.

CHAPTER XIX

LOWS ESPECIALLY ASSOCIATED WITH RAIN

The controls governing rainfall in Australia are not yet fully understood. There are obvious connexions between low pressures and rainfall—more obvious perhaps than between temperatures and rainfall. Yet previous chapters have shown that it is the *cooling* of a body of air which produces rainfall, so that one might think that temperature was a larger factor than pressure, which does not appear to be so vitally concerned.

But if we think for a moment, we shall see that it is the temperature at an elevation rather than that at the surface which is important. The Lows, which show where air is being sucked up (if Dines's views be accepted) and cooled, are therefore very good guides to indicate favourable regions where rain may be initiated. Until further data (enabling us to tell what is happening from 5,000 to 20,000 feet up) come to light, it will probably be found that the behaviour of the Lows in Australia is the most feasible way of forecasting rain.[1]

If we make a quantitative study of the systems which bring rain to the various regions of Australia (as in my study, *The Australian Environment*, 1918), we find that they may be grouped into nine main types. Some of these have previously been discussed, so that it will be understood that some types may merge almost imperceptibly into others.

Chief Rain-bringers in Australia

Type.	*Typical Chart.*
1. Tropical Low on north-west coast	8 January, 1914 (see Fig. 153).
2. Tropical low-pressure belt in north	6 January, 1913 (see Fig. 8).
3. Tropical passing south-east to Antarctic	5 May, 1910 (see Fig. 154).
4. Tropical loop or tongue	7 March, 1910 (see Fig. 156).
5. Tropical trough	19 January, 1914 (see Fig. 157).
6. North-east cyclone	29 January, 1910 (see Fig. 158).
7. East coast Low	14 May, 1913 (see Fig. 160).
8. Antarctic surge	15 October, 1913 (see Fig. 161).
9. Rains with a High (non-isobaric)	20 June, 1910 (see Fig. 162).

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[1] An important method of forecasting for rain, based on temperatures, has been devised by my colleague Mr. E. T. Quayle, and is to be published shortly.

1. North-west Low, 8 January, 1914. The heaviest rains in the north-west of Australia usually accompany some such storm as is illustrated in Fig. 153. This Low developed at Cape York, and then moved to the west as is shown in Fig. 149 previously. It moved very slowly, taking eleven days to reach Broome, and giving copious rains in the vicinity of the centre. On the 9th and 10th (of January, 1914) it passed over Roeburne and Onslow, and then merged into the indefinite low pressure (the so-called convection dome) of Pilbarra. On the 9th no less than 8·45 inches of rain fell at Onslow. The wind was westerly along the coast, and the rains were probably due to thermal or dynamic up-draught (and consequent cooling) and were not topographic.

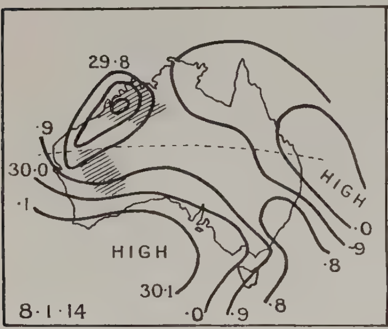

Fig. 153. North-west Low giving rains on coast. The track of this Low is given in Fig. 149 previously.

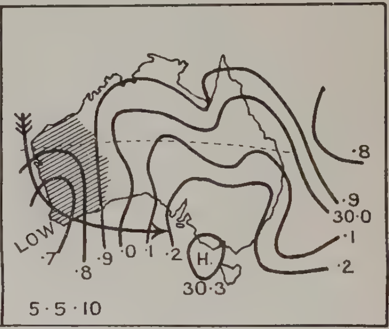

Fig. 154. Winter tropical moving to south-east. The arrow shows the track of the storm from 4th to 7th.

2. Low-pressure Belt in North, 6 January, 1913. This type has been discussed fairly completely in the second chapter, where it is used to illustrate the chief characters of a tropical Low (see Fig. 8). It developed from a 'convection dome' which lay over Pilbarra on the 3rd and 4th of January, 1913. Heavy rain fell to eastward, and the Low seems to have followed close after it. Probably, as I suggest elsewhere, the up-draught was more complete in the upper layers than at the surface—and the cyclonic circulation shown on the map is the base of a cyclonic whirl whose summit has advanced farther to the east than has the base. Heavy rain fell in the arid interior from this storm. Thus Peak Hill (W.A.) received 224 points and Cue 219 points.

3. Winter Tropical passing to South-east, 5 May, 1910. This type (moving along the coast) is not unusual in the cooler months, and may give good rains to the arid coast of West Australia. A loop had been hovering around Pilbarra for some days, and may have been involved in the Low which formed near North-west Cape on the 4th. This gave some rain to Carnarvon. Next day (see Fig. 154) heavy rains fell from Roeburne to Albany. On the 6th a trough formed along the coast—the west boundary being an oncoming High. The rain was confined to the south-west corner of the State.

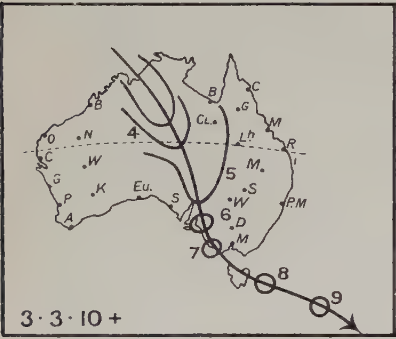

Fig. 155. Initial stages in a large tropical tongue. This developed into a closed (tongue-tip) cyclone on the 6th (see Fig. 156).

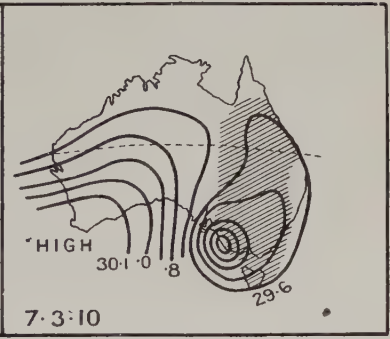

Fig. 156. A closed cyclone developed at the tip of a broad tropical tongue.

4. Tropical Loop or Tongue, 7 March, 1910. The initial stages in this storm—which gave rain to almost the whole of eastern Australia—are shown in Fig. 155. The somewhat indefinite area of low pressure in north Australia of the early days of March gave rise to a loop. This advanced southward accompanied by very heavy rain. Thus on the 3rd Alice Springs was the centre, on the 4th William Creek, on the 5th Farina, on the 6th Morgan. Here again there seemed a tendency for the *centre* of low pressure to *follow* the rain, as has so often been noted (see Fig 150).

The weather chart for the 7th is given (Fig. 156), and shows heavy rain from Cooktown to Tasmania.

5. Tropical Trough, 19 January, 1914. This trough developed from an indefinite low-pressure loop over Cloncurry on the 14th. A bulge protruded to the south-east on the 15th, 16th, and 17th,

with rain chiefly on the east coast. In the map shown (Fig. 157), all the eastern half is benefited as the trough is 'broken through' to the south. This probably implies that a larger stream of warm moist air is transferred to cooler regions. We do not fully understand the mechanism of the rainfall. Perhaps the warm stream flows over the cold dense southern layers and so is condensed. Perhaps the trough is merely a surface feature and pronounced up-draught is occurring in upper layers. (This feature is discussed in the chapter on the origin of the Low.)

6. North-east Cyclone, 29 January, 1910. This is an example of the wandering storms which come to us from the Solomon Islands or perhaps farther. They often give flood rains on the north Queensland coast—and may develop into hurricanes. Their parabolic path is shown by the broken line in Fig. 158.

From the 26th to the 30th the centre remained continuously over the northern highlands, and some low pressures (such as 29·37 at Townsville on the 29th) were recorded. At Townsville the following rain-gauge amounts were recorded from the 23rd to the 29th: 118, 77, 151, 114, 105, 532, and 109 points respectively. The rain fell intermittently in heavy squalls, the wind being generally from the south-east.

7. East Coast Low, 14 May, 1913. This type is very characteristic of the coast south of Brisbane, especially in autumn. Thus in May 1913 there were three such Lows on the 7th, 14th, and 26th respectively.

On the 12th May a High covered Australia. The only sign of the approaching storm was a heavy rain near Rockhampton and a very slight bulge in the isobar there (see Fig. 159). On the 13th a loop extended south-west to Bourke and rain fell strongly all round Brisbane. On the 14th (Fig. 160) a closed cyclone formed just south of Brisbane, and 166 points of rain fell at the capital. Thereafter it passed to the east.

8. Antarctic Surge, 15 October, 1913. Storms developing far to the south of Australia surge northward and affect our southern coasts especially in winter. We are not able to chart most of the Antarctic Low, and often have but little warning of the approach of these storms. As discussed elsewhere, there is a strong tendency for an Antarctic to link up with a tropical trough. Such a case is illustrated in Fig. 161.

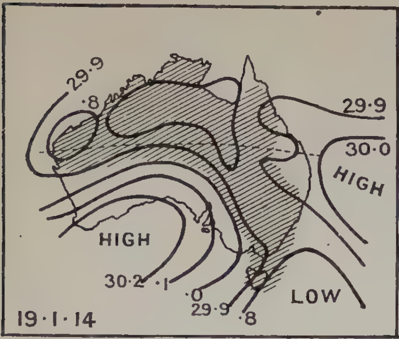

Fig. 157. A broad tropical trough developing from a Cloncurry loop, giving rain through east Australia.

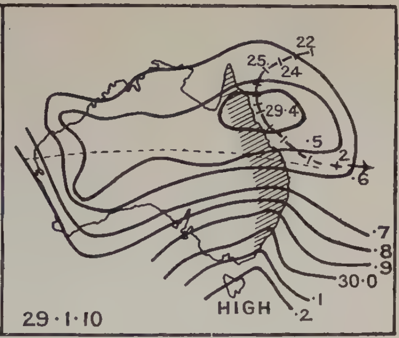

Fig. 158. A north-east cyclone giving rain to Queensland coast. The broken line (and dates) shows its track.

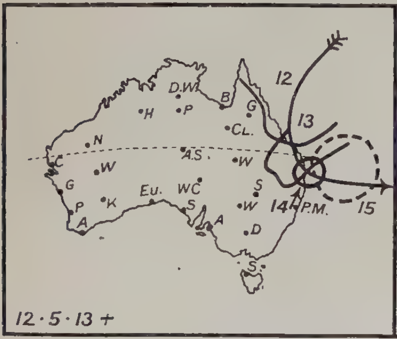

Fig. 159. The development of an east coast cyclone, shown approximately by the front loops and central isobars on four days.

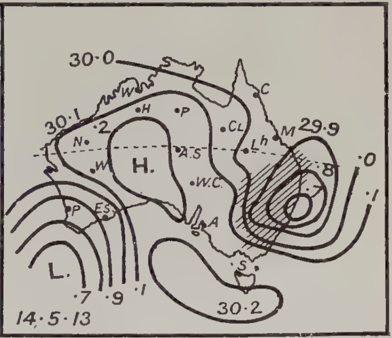

Fig. 160. An east coast cyclone affecting New South Wales.

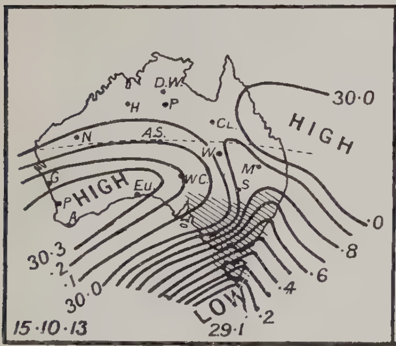

Fig. 161. Antarctic surge which has moved up towards a tropical trough.

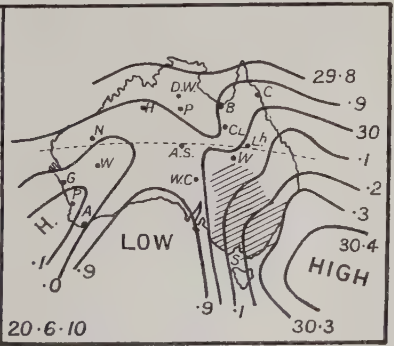

Fig. 162. Rains in the south-east, with a long-lived High.

On the 12th October a large low-pressure area around Pilbarra surged southward a little and a trough then opened to the south. This moved to the east with a Low with moderate gradients occupying the southern opening. On the 15th an intense Low surged northwards, with its centre somewhere about Macquarie Island. Here a pressure as low as 28 inches was recorded.

Fairly heavy rains fell throughout Victoria on the 14th and 15th.

9. Rains with High Pressures, 20 June, 1910. From the 14th to the 22nd June a High dominated south-east Australia. Rain fell, without any apparent connexion with a Low, on many days. Thus on the 15th there was some rain near Alice Springs; on the 16th it extended to Port Augusta. On the 17th it reached from Cloncurry to Melbourne, and on the 18th it affected western Victoria. In Fig. 162 is shown the rain for the 19th and 20th; and on the 21st it extended from the Bight to Cape Howe.

This set of charts is almost unique, for it is a rare thing to get any *inland* rain with a High controlling the weather. On the coast the ascent of air over a mountain often gives showery weather—whatever may be the pressure control—but the above example is not of this type. Usually one can foretell from such rains the approach of tropical cyclone or similar control, but this is not the case here.

It is therefore inserted as a most unusual example, and not as a type which is likely to occur frequently.

REGIONAL DISTRIBUTION OF RAIN STORMS (1910–14)

(Figures give percentages of whole number of days of widespread rain.)

A. TROPICAL AUSTRALIA (mostly summer rain)

Index	*Region.*	*Tropical Lows.*			*Trough.*	*Indef.*	*Highs or Non-Isobaric.*
		Over the Region.	*West of Region.*	*East of Region.*			
W1	Tropical W.A.	**33**	19	16	11	17	4
K1	Northern N.T.	**37**	13	14	12	24	—
K2	Southern N.T.	20	7	6	**54**	14	—
Q1	NW. Queensland	23	22	—	**30**	22	3
Q2	NE Coast, Q.	20	24	—	24	—	**33**
Q3	Brisbane and New England	15	—	25	**43**	—	16

B. TEMPERATE AUSTRALIA (mostly winter rain)

Index.	*Region.*	*Tropical Lows.* Over Region.	*West of Region.*	*East Coast.*	*Trough.*	*Loop.*	*Antarctic.*	*High or Non-Isobaric.*
W2	Arid Coast	**29**	18	—	18	—	**27**	8
W3	Arid Centre, W.A.	—	11	—	17	**29**	**34**	10
W4	Swanland, W.A.	11	—	—	10	—	**73**	6
S1	Lake Eyre	10	—	—	**64**	—	20	6
S2	Adelaide	10	—	—	24	13	**47**	6
N1	Inland N.S.W.	—	—	13	**47**	19	13	8
N2	SE. Coast	—	—	**20**	21	12	17	6
V	Victoria	—	—	13	22	14	**46**	5
T	Tasmania	—	—	5	**40**	5	**40**	10

The foregoing table epitomizes our discussion of relation of rain to isobaric systems. It is derived from the quantitative study I made in the memoir, *Australian Environment* (1918 Melbourne). The first column refers to the index letters on the map (Fig. 163). (Charts for these types are given in Figs. 152–62.)

In tropical Australia the chief rains in the *west* and north accompany Lows over the region concerned. In the *centre* and *south-east,* troughs are the chief rain-bringers. On the *north-east* coast, the Highs are much the most favourable, but this is purely because they furnish south-east winds blowing from the sea up the coastal ranges.

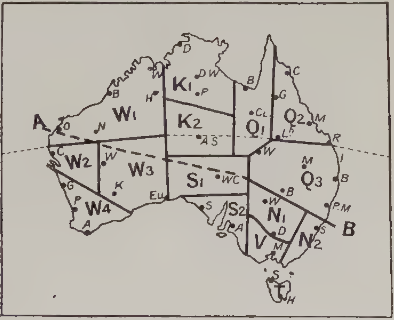

FIG. 163. Key map to rain regions in the Table, showing the dominant pressure controls accompanying rain. AB shows the line separating summer from winter rain regions.

In temperate Australia conditions are quite different. Only on the *arid coast* of West Australia is the local Low the chief instrument. In the *centre,* troughs and loops are the chief controls. But the Antarctics are the dominant feature in the arid centre of West Australia, in Swanland (W.A.), in the Adelaide region, in Victoria, and in Tasmania. In the *south-east* corner, east coast Lows and troughs are of about the same importance.

CHAPTER XX

THUNDERSTORMS[1]

These phenomena are perhaps of greater importance in Australia than in most other regions of white settlement—because our arid tropical areas are very largely dependent on them for their rainfall.

Milham defines a thunderstorm as follows :

> 'An immense cumulo-nimbus cloud accompanied by copious precipitation, a marked drop in temperature, and a peculiar outrushing squall wind which just precedes the rainfall. Thunder and lightning are always present, and hail sometimes falls. It is a violent, local storm, covering a comparatively small area, and lasting but a short time.'

The two most impressive features are the lightning and the thunder. These are, however, not the causes but merely results of the thunderstorm. The chief agents are the heat and moisture.

Lightning. The Englishman Hawksbee (early in the eighteenth century) is credited with *first* suggesting the relationship between lightning and electricity. About 1750 Winkler in Leipzig and Franklin in U.S.A. brought the matter into the domain of practical science.

There are several varieties of lightning, the most common being the 'zig-zag' lightning, and the 'sheet' lightning. There is of course no foundation for the conventional shape of the lightning flash. When photographs of lightning are examined (see Fig. 164) it is seen that the word 'zig-zag' only poorly expresses the course of the lightning. 'Branched' or 'forked' lightning would be a better term.

When a spark discharge from a large coil is examined, almost identical phenomena are observed. In the storm the lightning is a similar spark discharge from one cloud to another, or from a cloud to the earth.

Photographic records with a rotating camera show that the lightning flash is usually composite. The discharge passes out intermittently; gradually breaking down the resistance of the air, but producing branching discharges while so doing. Then, when a suitable path is open, the whole charge is dissipated in a succession of more direct flashes along one track.

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[1] The best recent account of thunderstorms is given by Professor Humphreys in the *Monthly Weather Review*, Washington, June 1914. I have used it freely in this chapter.

Dr. G. C. Simpson has shown that the electricity brought down by the rain consists of both positive and negative electricity, the former predominating 3·2 times.

Further, he shows that if distilled water falls through a vertical blast of air, charges of this kind are produced and carried down in the drops.

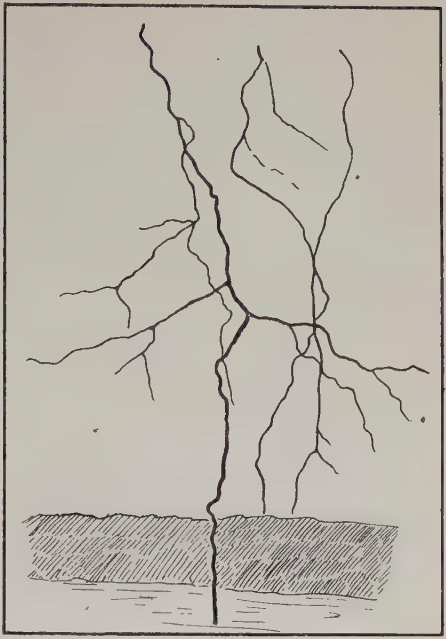

Fig. 164. Forked lightning. From a photograph at Sydney Observatory, 7 December 1893 (from Hann).

In a thunderstorm the up-rushing air full of moisture is thus the agent which produces the electricity. The lower portions of the cloud become positively charged and the negative electrons are chiefly carried up to the highest portions of the cloud. The earth is always negatively charged; hence the intermediate (lower cloud) positive layer may discharge to the ground, or the negative portion above, or to another cloud.

Thunder is the result of an atmospheric explosion. The air is intensely heated by the discharge and expands enormously. Hence it generates a compression-wave which passes outwards from the whole length of heated air. The rumbling is due chiefly to the varying distances of the portions of the flash, and not so much to echoes from the clouds or from the ground.

Sheet lightning without thunder is common in the evening in hot regions. It usually appears near the horizon, and may be due to far distant storms whose thunder is not heard but whose flashes are reflected on the clouds.

ORIGIN OF THUNDERSTORM. As we have seen, the rapid up-rush of moist air is the essential condition of the thunderstorm, as it is of the cumulus cloud. And this explains why the former may be regarded as an overgrown cumulus.

> 'The cause of the violent up-rush and turbulent condition within large cumulus clouds is presumably the difference between the temperature of the inner or warmer portions of the cloud itself, and that of the surrounding atmosphere at the same level' (Humphreys).

Whatever increases this difference of temperature in adjacent columns of air will therefore increase the abundance of thunderstorms. Wherever convection is greatest there we shall find most examples.

In the doldrums, thunderstorms are of daily occurrence, and their number decreases as we approach the Poles. In Brazil (Para) there are about 170 days in the year with thunderstorms, at Batavia 95, in Florida 50, at Irkutsk 6, and Iceland 1.

They are more numerous near mountains than on the plains or oceans. Hann gives the following table for the Indian Ocean:

	South Latitude.				
	34°–36°	36°–40°	40°–44°	44°–48°	48°–50°
Percentage of days of observation . .	12	4·5	4·3	2·5	0

VELOCITY. The thunderstorm moves generally with the velocity of general air-drift. Hence in temperate regions they pass to the east with a velocity of about 25 miles per hour. But in a peninsula like Florida it is found that they move *away* from the land with the prevalent offshore wind.

SEASON OF YEAR. They occur chiefly in the hottest months of the year, though as moisture is a determining factor if the summer is a dry season this may affect the number of thunderstorms.

In Fig. 165 three typical localities are given. Thus Melbourne with a uniform rainfall has most lightning (and also most thunderstorms) in summer, but they are relatively numerous also in winter. In Brisbane, which has a much greater rainfall in summer than in winter, the thunderstorms are correspondingly more abundant. In Perth, with a dry summer, the most thunderstorms are in the *cooler wet season*, with a maximum in July.

Time of Day. They are most numerous during the hours when convection is strongest, i.e. from 2 p.m. to 4 p.m. The following table (from Hann) shows the variation in Scotland and over the Indian Ocean from the Challenger Records. The maximum over the ocean occurs in the early morning, because then convection is more marked.

	Midnight–4.	4–8.	8–*noon.*	*noon*–4.	4–8.	8–*midnight.*
	%	%	%	%	%	%
Scotland .	11·5	8·0	12·0	26·0	25·0	18·0
Ocean .	33·0	22·0	6·5	11·0	6·5	20·0

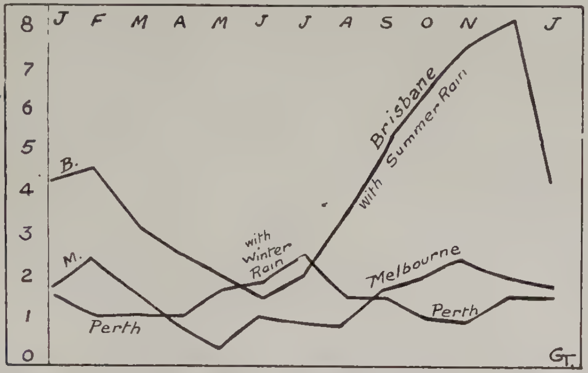

Fig. 165. Average monthly records of lightning. (Figures are days per month.)

Structure of a Thunderstorm. Humphreys gives two suggestive diagrams, which I have copied in Figs. 166 and 167.

In the first (Fig. 166) the cumulus cloud is moving to the east, but no rain is falling. Most of the air entering the cloud does so through its front under-surface. In Fig. 167 is shown a well-developed thunderstorm in progress. The warm ascending air is in the region A; the cold descending air at D; the dust cloud at D^1, the squall cloud at S, the storm collar at C, the thunder-heads at T, the hail at H,[1] the primary rain due to initial convection at R. Secondary rain may fall in the rear of the storm owing to the coalescing and quiet settling of drops where the winds are no longer active.

The change in direction of the front *surface* wind is due largely to the chilling of air by the hail and by evaporation of the falling rain. It sinks down to the surface and maintaining its original velocity to the east it becomes a surface wind moving from the storm (as at D^1 in Fig. 167).

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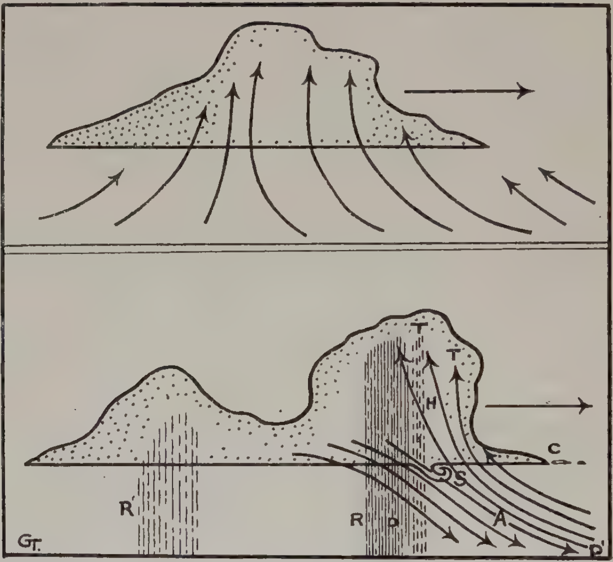
[1] The repeated changes in elevation in portions of the cloud often cause the hail to form in layers about a solid nucleus, as the hail stone rises and freezes or sinks and melts.

Between the descending cold column associated with the rain, and the ascending warm air in front, a horizontal vortex is formed (as at S). Here the warm air is locally chilled and a small cloud roll can sometimes be seen rotating as shown.



Figs. 166, 167. Above are shown the principal air movements in the formation of a cumulus cloud. Below is an ideal cross-section of a typical thunderstorm. (Both after Humphreys.)

Types of Thunderstorm. Humphreys gives three main types:

(*a*) Heat thunderstorm due to local convection and always occurring in the hottest hours of the day. They are the chief type in Australia, and the only common type in the tropics.

(*b*) Cyclonic thunderstorm found in the north-east quadrant of a Low.[1] It is due to crossed currents of air. The surface air is chiefly from warm latitudes. The upper air comes largely from the west or south-west. Hence the vertical temperature gradient may be greatly affected under favourable conditions. This type is commoner in the cooler regions.

---

[1] In the Southern Hemisphere.

(*c*) The line squall. This is a series of thunderstorms formed along the trough of a **V** depression where conflicting air currents are usual. They may develop into tornadoes.

THE BRISBANE THUNDERSTORM OF DECEMBER 1912. One of the most striking storms of recent years is described in the Australian *Monthly Weather Report* for December 1912. With the isobaric conditions shown in Fig. 168 there had already been severe thunderstorms with hail all through the south-east of Queensland. They were associated with a trough between two Highs, the latter being centred over the Bight and over New Zealand.

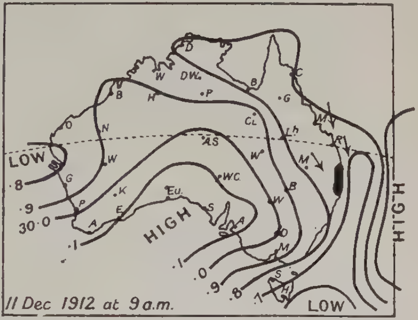


FIG. 168. Thunderstorms associated with a line squall in south-east Queensland.

The Brisbane barogram (see Fig. 169) showed a steady decrease to 12·45, but curiously enough the forenoon was not especially muggy, for the humidity was only 50 per cent. and the temperature 86° near noon.

> 'Towards noon heavy storm clouds gathered to westward of Brisbane, and distant rumblings of thunder were heard in that direction. At 1 p.m. the sky looked very ominous over the western suburbs, the clouds having that dirty greenish appearance which usually presages a heavy fall of hail. Very soon the characteristic outrushing squall burst upon the city in all its fury, accompanied by terrific claps of thunder and most vivid lightning, and reached the central portion about 1·45 p.m. Light rain and small hail fell just at first, but very quickly there was a perfect deluge, which continued until 2 p.m. By 3 p.m. the rain had passed to eastwards.'

The barograph showed a peculiar increase of 0·18 inch in about 15 minutes when the torrential rain was falling. The pluviograph showed a rainfall of 1·65 inches, of which 1·45 inches fell between 1·50 and 2·15 p.m. The temperature fell 18°. At Double Island Point, 105 miles due north of Brisbane, the barograph showed the more characteristic drop with the oncoming thunderstorm (see Fig. 169).

The storm was evidently of the 'line-squall' type, with a front extending from Gympie for 200 miles south to Grafton. The general movement was to the east-north-east.

The Southerly Burster. This is the most interesting of the local winds of Australia. Although it is not primarily a convection wind, it has some likeness to the thunderstorm and so may be considered here.

This phenomenon has luckily formed the subject of one of the few detailed studies in Australian meteorology. The prize essay by H. A. Hunt (published in Sydney in 1896) gives a very complete account of their characteristics, and I have borrowed largely from it.

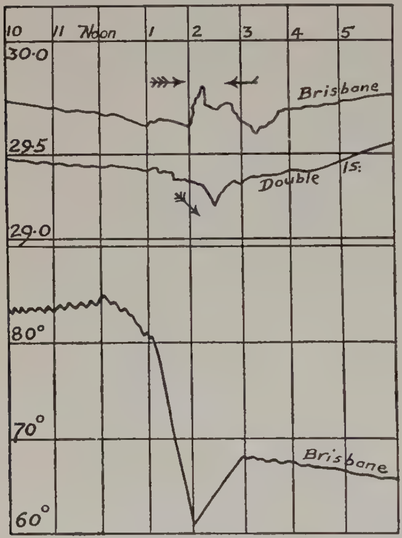


Fig. 169. Barograph records at Brisbane and Double Island Point; and thermograph at Brisbane, 11 December, 1912.

Description. The burster is preceded by a period of high temperature varying from three hours to three or more days, accompanied in the early part of summer or towards its close by wind from the west or north-west, and in midsummer months generally from the north-east. As the hour of the outbreak approaches there begin to accumulate in the south, ball-shaped cirro-cumulus clouds, and frequently—if electric disturbances are to accompany the squalls—heavy cumulus thunderclouds rise gradually in the south-west.

'An hour or so before the squall, a heavy cumulus roll appears low down on the southern horizon. . . . It is from thirty to sixty miles in length. . . . As it approaches careful observation shows a light (cloud) fringe rising from underneath it in front, falling over the top, and trailing behind the advancing cloud.

'The wind drops suddenly and a profound calm prevails for a short time. Clouds of dust arise to the south . . . the wind-vane flies round to the south, and in a few moments it is blowing with the force of a gale.'

A burster rarely brings immediate rain, except when it is accompanied by a thunderstorm. The chief rain often falls on the second day of the blow. They always produce a fall of temperature, usually about 18°.

The chief characters are therefore the long cloud roll, the sudden sharp change of wind direction, the strength of the south wind, and the large drop in temperature.

Locality. The most typical examples occur on the coast of New South Wales between Cape Howe and Port Macquarie. The city of Sydney is thus right in their path, and the advent of the cool change is anxiously awaited in the height of summer.

Their seasonal distribution is shown in the graph in Fig. 170. They are most abundant in summer, but it is interesting to note that spring is more favourable than autumn. The latter is markedly the rainy season on the Sydney coast, so that the burster is not a feature of the wet season. Mr. Hunt's data show that they reach Sydney (from the south) most often between 6 p.m. and midnight, and are least common at noon.

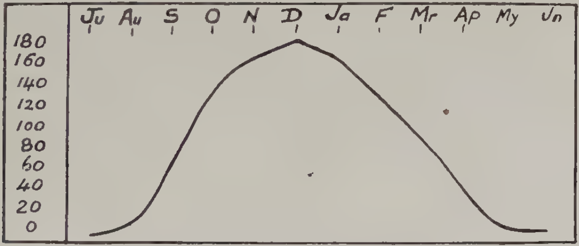


Fig. 170. Frequency of southerly bursters at Sydney, 1863–94 (based on H. A. Hunt). All sudden shifts of wind to the south—with continued velocity—are included.

The southerly winds are usually felt first near Gabo Island in the extreme south, and then the effect moves up the coast at rates varying from 10 to 60 miles an hour. The velocity of the wind at Sydney is usually about 30 miles an hour.

A fairly typical southerly burster is illustrated in the two charts for the 8th and 9th of March 1915 (Figs. 171, 172).

For some days hot north winds had been blowing at Sydney towards the low pressure south of Australia. On the 8th the maximum temperature at Sydney was 100·7° F.

Meanwhile the high pressure over West Australia had been advancing extremely rapidly—moving about 1,300 miles in 24 hours, which is more than double the usual rate. The New Zealand High kept about the same position. Hence the Low was squeezed down to the south-east and at

3·10 a.m. on the 9th the welcome southerly reached Sydney with a maximum velocity of 28 miles per hour.

The temperature fell greatly and the maximum on the 9th only rose to 79° F. The hot tongue (shown by the ruled areas in Figs. 171, 172) retreated before the south winds into central Queensland.

The special features of the burster are, however, largely due to the topography. The winds are blowing over the rugged highlands of the south-east of Australia, and suddenly reach the relatively smooth ocean surface lying clear along their track.

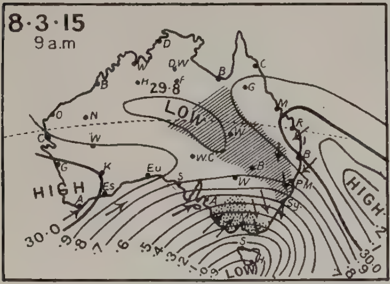


FIG. 171. Hot north winds affecting Sydney on the day preceding a southerly burster. Ruled lines show maximum over 100° F. Dotted areas show maximum below 80° (where southerlies blow).

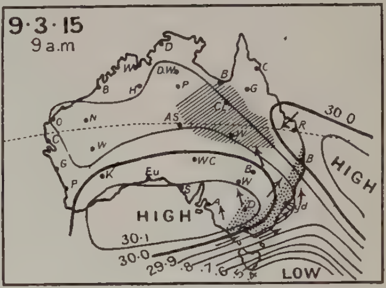


FIG. 172. Cool southerly burster at 3 a.m. at Sydney. (Dotted areas show maximum temperature below 80° and ruled areas over 100° on the 9th).

Other factors are discussed in the memoir by H. A. Hunt, to which the student is referred.

Hann (in his *Klimatologie*) gives some interesting comments on the southerly burster. He points out that the violent south-west wind is analogous to the north-west wind of the 'Boe' (a variety of line squall) in Germany. The temperature changes are more striking in the warmer region. The 'Pampero' of south Brazil is almost an exact counterpart of this storm.

SOME RECENT SOUTHERLY BURSTERS

Date.	*Time of Burst.*	*Maximum Velocity.*	*Time.*
1914 Nov. 26	11·40 p.m.	27 miles	
Nov. 28	1·40 a.m.	26 ,,	7·45 a.m.
Dec. 14	1·5 p.m.	28 ,,	2·15 p.m.
1915 Jan. 4	8·35 p.m.	28 ,,	
Feb. 3	3·40 p.m.	23 ,,	6 p.m.
Feb. 5	11·45 a.m.	30 ,,	
March 1	10·40 p.m.	30 ,,	

CHAPTER XXI

TORNADOES AND HURRICANES

'The most violent atmospheric phenomenon with which man has to contend is the tornado. Its wind velocities are greater than those of the dreaded tropical cyclone. Its strength is superior to that of any structure which man may build to withstand it.

> 'It is a very intense progressive whirl of small diameter, with inflowing winds which increase tremendously in velocity as they near the centre. From the violently agitated main cloud-mass above, there usually hangs a writhing, funnel-shaped cloud, swinging to and fro. With a frightful roar comes the whirl out of the dark angry west advancing with the speed of a fast train. Its wind velocities exceed probably 300 miles an hour, its path of destruction is usually less than a quarter of a mile wide. Its total life a matter of an hour or so.'[1]

Tornadoes are not common in Australia; but two of the most violent have occurred fairly recently in Victoria. In September 1911 a tornado swept the Marong district to the west of Bendigo. Its track is shown in Fig. 173.

'In the form of a long inverted cone of cloud the tornado started between Leichhardt and Derby about 2.30 p.m. and followed a serpentine course varying from 5 to 12 chains in width and about 12 miles in length, the whole of which was covered in half an hour.

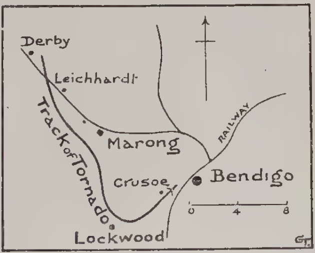


FIG. 173. Track of the Marong tornado in central Victoria on 27 September, 1911.

'Violent thunder and hail accompanied the storm, many of the blocks of ice which fell being of the shape and size of safety matchboxes, with the edges rounded off—while some were up to one pound in weight.'[2]

---

[1] 'The Tornadoes of U.S.A.', by Professor Ward, *Quarterly Journal of the Meteorological Society*, London, 1917.

[2] Australian *Monthly Weather Report* for September, 1911.

Near Marong a mine battery was completely demolished and the débris carried for miles. Many houses were wrecked along its course, but luckily it died away as it approached the suburbs of Bendigo.

Over an inch and a half of rain was recorded in a very short time at Lockwood.

Two days later similar conditions on the chart produced a tornado at Cudal near Orange (N.S.W.).

In Fig. 174 the weather chart accompanying the Marong tornado is given. A broad tropical trough had for some days been moving very slowly to the eastward. Rain fell all through the south-east on the 26th, and consequently a steady drift of moist warm air was passing over Victoria. Mr. E. T. Quayle had noted especially the abundance day after day of towering cumulus and cumulo-nimbus clouds.

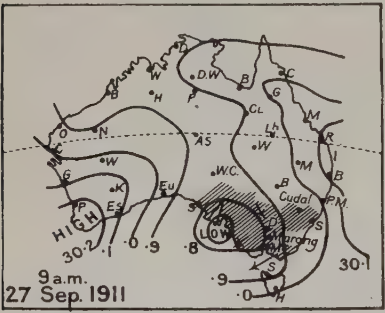


Fig. 174. Tornado at Marong, Victoria.

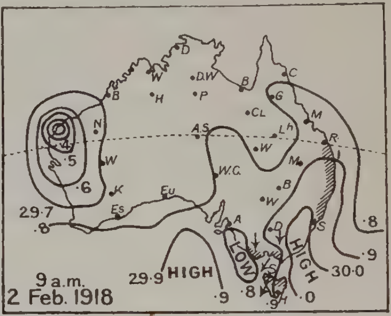


Fig. 175. Tornado at Brighton, Victoria.

The day of the storm at Marong was close and thundery, and gradually assumed a peculiar threatening blue-black appearance. The typical funnel-cloud was actually photographed, and is reproduced in the *Weather Report* cited.

The origin of the tornado is the same as that of a thunderstorm. Milham accounts for it by assuming a specially violent convectional up-draught.

> 'There would then develop a well-marked indraft at the earth's surface to replace the rising air. This moving air would be deviated owing to the earth's rotation and a vigorous atmospheric whirl would build itself up.'

The Brighton tornado occurred about 4.50 p.m. on 2 February, 1918. At least four of the officers of the Bureau experienced some of the effects, and the storm is to be fully described in a forthcoming memoir. The writer was at Tewksbury (see Fig. 176), just within the northern margin of the damaged region.

There was a little drizzle in the afternoon, which was dull and muggy[1] with heavy nimbus and cu-nimbus rolling across from the west. At 4.45 a ferocious gust of wind accompanied by heavy rain and much hail hit the house. The rain drove along horizontally, and the wind bent small trees flat and blew down large pine-trees in the direction shown by the arrows in Fig. 176.

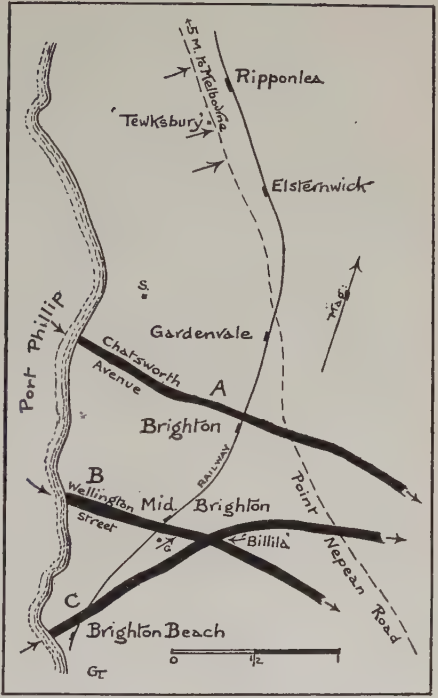


FIG. 176. Plan of the three tornadoes at Brighton, Victoria, on 2 February, 1918. The tracks extended much farther to the east into open country.

But the actual tornadoes—for there were three concerned—developed from 1½ to 3 miles south. Two whirls approached from over the bay—one heading for Brighton station and the other for Middle Brighton station. Many gables were torn down on both these courses—which passed through thickly clustered residences—and in Wellington Street and eastward large brick houses collapsed.

About five minutes later a third tornado appeared from the south-west and devastated the buildings near Brighton Beach station. This passed eastward, and where it crossed the earlier tornado's track (at Billila) a veritable orgy of destruction occurred. A whole avenue of trees blocked the road, and the large gardens of Billila were converted into a tangled maze of uprooted trees.

The peculiar vacuum effect of the tornado was noticed by the Commonwealth Meteorologist at his residence at S (on Fig. 176). The fanlights on the roof were lifted up by the normal air inside the house pressing out to the very low pressure accompanying the tornado.

---

[1] The hygrograph rose from 57% to 92% from 4·30 to 5 p.m.

At the old gasworks (G at Middle Brighton) heavy plates of sheet iron weighing 2 cwt. were carried 100 feet and hurled up into pine-trees to the north-east, with such force that the soft wood of the pine burst right through the 12-gauge iron.

Two people were killed in this visitation, which is by far the most striking example of recent years in Australia. It exhibited, however, very much less violence than many American tornadoes.

The weather chart for the 2nd of February is given in Fig. 175. Conditions were somewhat like those of the Marong occurrence, in that a trough lay between two Highs. Muggy weather following rain also characterized both storms, and in both there was evidently a strong flow of warm moist air from the north.

It is impossible to forecast when a tornado will develop from an overgrown thunderstorm, but the risk is small. Even in the 'tornado States' of U.S.A. (Kansas, Missouri, and Illinois) the probability of tornado destruction is less than that of lightning or fire, though there are about fifty tornadoes a year in U.S.A.

SOME AUSTRALIAN TORNADOES

Year.	*Date.*	*Place.*	*District.*	*Remarks.*
1904	July 15	Avenel	North-east Victoria	Moved NW. to SE.
1906	March 27	North Sydney	New South Wales	,, ,,
1908	July 30	Bondi	(Sydney)	Waterspout.
1910	Nov. 3	Laverton	Inland West Aus.	
,,	Nov. 4	Hergott	North of South Aus.	At 5 p.m. Barom. 28·40.
,,	Nov. 4	Richmond	Queensland	Two inches of rain.
,,	Nov. 5	Gemville	West of Bourke	One inch in half hour.
1911	Sept. 25	Marong	Near Bendigo	
,,	Sept. 29	Cudal	Near Orange	
1912	May 7	Port Macquarie	New South Wales	Waterspout.
1913	Jan. 28	Goolagong	Cowra (N.S.W.)	
,,	Nov.	Goolagong		
,,	Nov. 12	Murpa	Wilcannia (N.S.W.)	

HURRICANES

We have seen that convection gives rise primarily to a cumulus cloud. If this intensifies a cumulo-nimbus cloud is built up and usually a thunderstorm arises. This may increase in violence, and if conditions of temperature and moisture are favourable it may develop into a tornado.

On a far larger scale a somewhat similar movement of the air constitutes a cyclone—though, as we have seen, some of these are probably 'sucked up' from the earth's surface by a whirl *originating* in the upper air (see Chapter XVII). Under suitable conditions these beneficial quiet cyclones may develop into destructive areas of low pressure which are known as Hurricanes, Typhoons, or Willy-Willies. (The word '*cyclone*' should not be used for a *destructive* storm, for originally it only implied an area of low-pressure air characterized by more or less circular isobars and rotating winds.)

LOCALITIES. Hurricanes are practically confined to the regions between 10° and 30° of latitude on each side of the equator. They are best known in the Gulf of Mexico and in the China seas. But they also occur in the Indian Ocean, both north and south of the equator and in the Coral Sea between Queensland and Fiji.

It has been stated that they never occur on the east side of an ocean, but our West Australian hurricanes very effectively disprove this idea. They are not known in the south Atlantic, according to Milham. No better picture of a hurricane has been given than by the latter authority.[1]

> 'The first signs of the approach of the storm are to be found in both sea and sky. The sky is covered with a thin cirrus haze, which causes lurid red sunsets and halos or rings about the sun by day and the moon by night. The air is still, moisture-laden, sultry, and oppressive. The barometer rises unduly high, or remains stationary when the daily drop is expected. The wind disappears and the long rolling swell of ominous import appears on the ocean. Soon the barometer begins to fall. A breeze springs up, but the air is still sultry and oppressive. The wind increases and on the horizon the dark rain cloud, shield-like, has appeared.
>
> 'The barometer now falls with startling rapidity; the blue-black rain cloud rushes overhead; rain falls in torrents, cooling the air; the wind has increased to full hurricane strength, a hundred miles an hour or more; the sea is lashed to fury.
>
> 'This may continue many hours, when suddenly the wind ceases, the clouds break through, the temperature rises, the moisture grows less and the barometer is at its lowest, for the calm central eye of the storm has been reached.
>
> The respite is but brief, perhaps twenty or thirty minutes, when the wind changes to the opposite direction and increases to full hurricane strength as suddenly as it ceased. Rain again falls in torrents, and everything is as before except that the barometer is rising. After several hours the end of the storm is reached, the wind dies down, the rain ceases, the nimbus clouds break through . . . the wind is a gentle breeze. But for the wreckage and the ominous heaving of the ocean one would not know that a storm had passed.'

---

[1] Milham's *Meteorology*, New York, 1912, p. 267.

In Australia are two hurricane regions; one off the north-west coast, where the ports from Derby to Onslow are endangered; and the other off the Queensland coast from Cooktown to Mackay.

In the Australian *Monthly Weather Report* for May 1911 I give a list of thirty-one West Australian hurricanes recorded between 1877 and 1912. This list is somewhat condensed and reproduced herewith, together with a list of Queensland hurricanes.

SOME WEST AUSTRALIAN HURRICANES

Year.	*Month.*	*Date.*	*Chief Locality.*	*Max. Rain.*[1]	*Bar.*[2]	*Losses.*
1877	Feb.	15–18	Lacepede Is. (off Broome)	—	29·49	
1878	Dec.	24	,,	—	29·52	
1879	Jan.	25	Roeburne	—	28·92	*Sulina* and *Manfred.*
1880	Jan.	9	Yarnmadarra	—	—	*Adalia.*
1881	Jan.	7	Cossack		27·0	Many luggers.
1882	Mar.	7	Roeburne	6·5	28·1	More severe than 1872.
1887	Feb.	12	Cossack	8·5	29·2	
,,	April	22	Wallal	—	—	Over 200 lives.
1888	Jan.	7	Derby	17·0	29·13	
,,	April	22	90 Mile Beach	—	—	114 men lost.
1889	Mar.	1	Roeburne	6·0	—	Three boats wrecked.
1890	Jan.	27	Wyndham	11·6	29·36	
1897	Dec.	26	Onslow	6·5	28·57	Wrecked Onslow.
1898	April	2	Cossack	36·0	27·8	All Cossack boats lost.
1899	Jan.	12	Wyndham	9·0	—	*Tangier* record.
1900	Mar.	5	Cossack	13·0	29·34	
1901	Jan.	30	(South of Java)	—	29·36	*Australind* record.
,,	Feb.	7	Cossack	13·0	28·78	(Same as above).
1902	Feb.	9	Cossack	7·0	29·03	
1903	Jan.	10	East Kimberley	25·0	29·6	
1904	April	17	Broome	8·0	—	*Star of East* lost.
1905	Feb.	8	Onslow	7·0	29·11	Some loss of life.
1907	Jan.	8	La Grange	8·4	29·5	
,,	Mar.	13	Cossack	13·5	29·2	*Mildura* lost.
1908	April	26	La Grange	8·5	29·5	Fleet and 50 lives lost.
,,	Dec.	10	La Grange	8·5	—	*Cutty Sark* lost.
1909	Jan.	19	Onslow	8·8	28·9	Four luggers and 24 men lost.
,,	April	6	Onslow	6·0	29·2	
1910	Nov.	19	Broome	11·0	28·64	26 luggers and 40 lives.
1911	Feb.	7	Onslow	6·0	28·8	*Glenbank* and all crew but one.
1912	Mar.	6	Broome	8·7	29·3	
,,	Mar.	21	Cossack	9·0	28·86	*Koombana* and all crew.
1915	Feb.	26	Perth	—	29·13	Too far south to be typical.
1917	Jan.	7	Broome	14·0	29·42	Not destructive.[3]
,,	Mar.	14	Onslow	—	28·9	Not destructive.
,,	Mar.	27	Fortescue	—	—	Wrecked buildings.
,,	Dec.	17	La Grange	37·6	29·12	Not destructive.

[1] Heaviest record in the vicinity.
[2] Occasionally 9 a.m. and not lowest reading.
[3] Affected outlying regions chiefly.

SOME QUEENSLAND HURRICANES

Year.	*Month.*	*Date.*	*Chief Locality.*	*Rain.*[1]	*Bar.*[2]	*Losses.*
1870	Jan.	30	Bowen	—	—	Houses blown down.
,,	Feb.	20	Townsville	—	—	Town nearly levelled.
1878	Mar.	8	Cairns	—	—	
1884	Jan.	30	Bowen	—	—	Town unroofed.
1890	Mar.	24	Townsville	—	—	
1896	Jan.	26	Townsville	17·2	29·27	*Sigma* gale.
1898	Feb.	4	Mackay	—	—	
1899	Mar.	5	Bathurst Bay	—	—	Pearling fleet and 300 men.
1903	Mar.	9	Townsville	—	28·5	
1906	Jan.	28	Cairns	—	—	Town devastated.
,,	Mar.	4	Croydon	—	—	Town devastated.
1907	Jan.	19	Cooktown	—	—	Town devastated.
1908	Mar.	12	St. Lawrence	7·1	29·27	Damage to north.
1911	Mar.	16	Port Douglas	12·0	29·6	Town levelled.
,,	Mar.	24	Flat Top	—	29·7	S.S. *Yongala* lost.
1912	April	6	Innisfail	32·6	29·8	
1913	Jan.	30	Cairns	8·2	29·1	*Innamincka* wrecked.
1915	Feb.	6	Mackay	11·5	29·38	Curved off shore.
1916	Dec.	27	Townsville	12·8	29·6	61 drowned at Clermont.
1918	Jan.	20	Mackay	24·7	27·5	Town largely wrecked, 20 lives lost.
,,	Mar.	9	Innisfail	16·6	27·8	Town wrecked, 18 lives lost.

[1] Heaviest rain recorded in vicinity.
[2] Occasionally 9 a.m. and not lowest reading.

FREQUENCY. These hurricanes are distributed through the months as follows :

WEST AUSTRALIAN HURRICANES

November .	1910	1
December .	1878, 1897, 1908	3
January . .	1879, 1880, 1881, 1888, 1890, 1899, 1903, 1907, 1909	9
February .	1877, 1887, 1901, 1902, 1905, 1911	6
March . .	1882, 1889, 1900, 1907, 1912, 1912	6
April . .	1887, 1888, 1898, 1904, 1908, 1909	6

QUEENSLAND HURRICANES

January . .	1870, 1884, 1896, 1906, 1907, 1913	6
February .	1870, 1898	2
March . . .	1878, 1890, 1899, 1903, 1906, 1908, 1911, 1911	8
April . .	1912	1

Hence it is obvious that they are practically confined to the hottest months, January being the favourite on the west coast and March on the east coast.

In Fig. 177 some of the more important storm-tracks are plotted. They all seem to originate near latitude 10° S., and then move to the south-west. The Port Douglas hurricane (16 March, 1911) is an exception, for it moved to the south-east.

Between latitudes 15° and 24° they almost all curve around in a parabolic path and then proceed to the south-east. Here again there are a few exceptions, as in the Port Douglas storm and the Bathurst Bay storm (of 5 March, 1899). Both of these (in north Queensland) passed to the west.

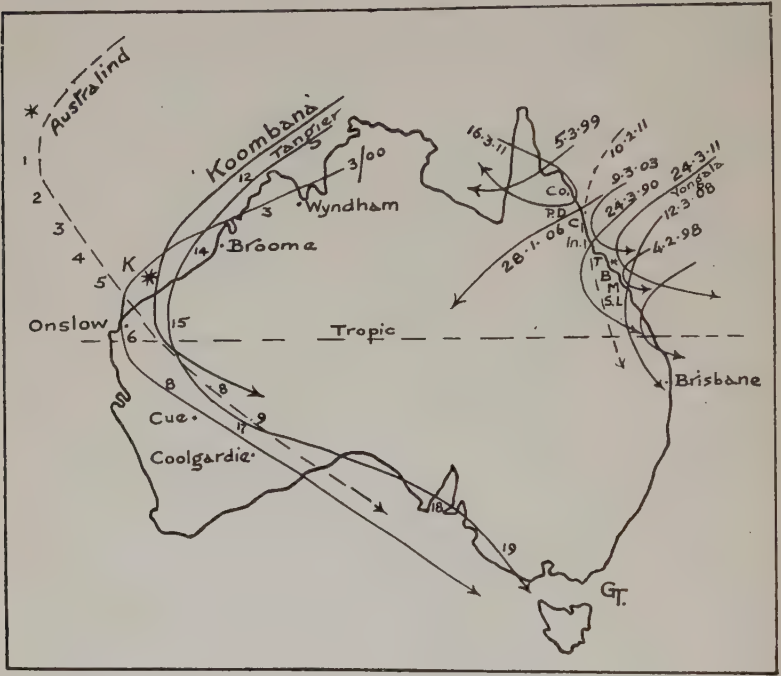


FIG. 177. Some Australian hurricanes. They lose their violence south of the tropic. Initials in Queensland indicate Cooktown, Port Douglas, Cairns, Innisfail, Townsville, Bowen, Mackay, and St. Lawrence. (See also Fig. 179.)

The violent phase of the storms often lasts for hours, and the storms themselves occasionally endure for days—so that we are dealing here with a phenomenon very different from the local convection-fed whirl which constitutes a tornado.

ORIGIN OF HURRICANES. Two theories have been put forward, and our knowledge is still too meagre to rule either out of court. The convection theory[1] supposes a mass of warm moist air to ascend in some favourable locality. Rain is precipitated and the latent heat set free causes a still greater ascent. The colder air moves in toward the region of convection, and gradually an energetic swirl is set up in somewhat unstable equilibrium.

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[1] Milham's *Meteorology*, p. 278.

The favourable localities are in the ' doldrums ' near the equator, where the air is not mixed by strong winds and where heat and moisture are abundantly present. When initiated the eddy moves to the west with the dominant drift of the hot belt, and then curves to the left (in the southern hemisphere) and gradually passes to the south-east in accord with the upper-air drift of sub-tropical regions.

The other theory is advanced by Fassig;[1] and here great stress is laid on the position of the ' centres of action of the atmosphere '. These are the semi-permanent Highs and Lows which have been discussed earlier.

Applying the theory to the southern hemisphere—the Low over north-west Australia produces north-west winds near New Guinea in midsummer. Farther south the south-east trades blow strongly. The force of these opposing winds is very high—giving rise to conditions favourable for the formation of a cyclone circulation.

Probably, as in most cases of considerable difference of opinion, there is much truth in both theories, and a combination of the two agencies may most often suit the case off Queensland. But off north-west Australia there is no such opposition of permanent winds.

The two divergent hurricanes shown in Fig. 177 seem to indicate that a storm generated sufficiently far north *drifts to the west*, and these may supply the western field.

In other words, both the systems of hurricanes originate near the Solomon Islands. Fassig, however, places the birth of the West Indian hurricanes off Senegambia. So that our storms may sail along south of the equator from very far east, and only occasionally develop hurricane force on reaching Australian waters.

In the Australian *Monthly Weather Report* for March 1910 is described the Fiji hurricane of 24 March, 1910. This originated near Samoa, wrecked districts in Fiji, in the Loyalty Islands and Noumea, and damaged Norfolk Island and the north-east of New Zealand.

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[1] Fassig, *Hurricanes of the West Indies*, Washington, 1913.

In the *Monthly Weather Report* for March 1912 the ‘ Koombana ’ hurricane is described much as follows :

Not much more than a fortnight earlier (on the 6th) a willy-willy had visited Broome (see the list of hurricanes, above).

The second ‘ willy-willy ’ was much more destructive to shipping and property, and caused the loss of the s.s. *Koombana,* with the whole of her passengers and crew. The first indications of this storm were shown on the 16th off Port Darwin (see Fig. 177), the barometer there reading 29·55 inches, with a light easterly wind. From that date to the 21st it can be traced passing in a south-westerly direction some distance off the coast, and at 9 a.m. on 21st a fresh easterly gale was blowing at Cossack, and the barometer stood at 29·576 inches. At 11.30 a.m. it began to fall suddenly, and continued falling until 11.30 p.m., reaching 28·866 inches, after which it remained stationary until 2 a.m. on 22nd, when it commenced to rise, and at 9 a.m. stood at 29·458 inches, with a strong west wind (see Fig. 178).

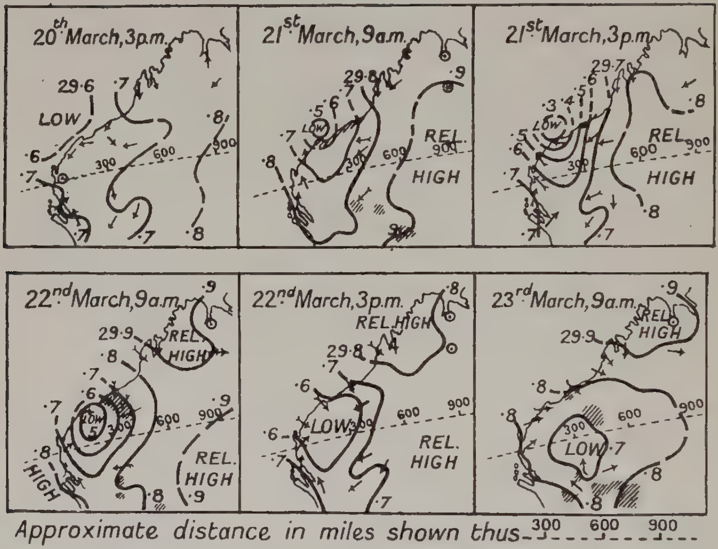

FIG. 178. Weather charts for the *Koombana* hurricane of March 1912. (From the *Monthly Weather Report.*)

More damage to property was caused at Whim Creek and at Balla Balla, 40 miles to the east, than at Cossack. The rainfall was very heavy, and ranged from 6 to 13 inches between Cossack and Fortescue River, and it extended inland in a south-easterly direction. The most remote rain stations, Ethel Creek and Balfour Downs, about 200 miles from the coast, registered 5·59 inches and 3·46 inches respectively. Light falls were reported over the north-east of the gold-fields, and the storm lingered over the tropics till the end of the month (see Fig. 179).

The following account, published in the *Hedland Advocate*, may be of interest:

'Judging from all available information, historical and traditional, relating to "willy-willies" on this coast, it would appear that the one just past (20–23 March) is without a parallel in its extraordinary characteristics of violence and destruction. There is no account of any "willy" equalling this in its various phenomena of suddenness and severity of power.

'It was preceded by hot, stifling days. On the Monday, the 18th, several divers, who have been years on this coast, warned their masters that there were sudden changes of hot and cold water below, with a ground swell, which, although the surface of the sea was calm and the glass good, they declared indicated the approach of a blow. (A similar warning was given by old divers two days before the disastrous Broome blow.) Quite suddenly on Tuesday night a strong "cockeye"[1] blew up from the east, followed by moderate winds and a little rain. On Wednesday, the 20th, the wind shifted slightly to the south, increasing in its strength, and by midday it was again blowing from the east—all through blowing in gusts, accompanied by occasional showers. By the time the *Koombana* and *Bullarra* had left Hedland, at 10.30 and 11.30 a.m. respectively, it began to excite alarm, luggers moved up the creeks, and people bolted up their houses. Two or three layers of swiftly-racing clouds could frequently be seen through the prevailing mist. It blew with terrific force whenever the wind shifted its course, and Hedland miraculously escaped its full force, but the *Bullarra* struck its fury three hours out, and the *Koombana* must have struck it earlier.

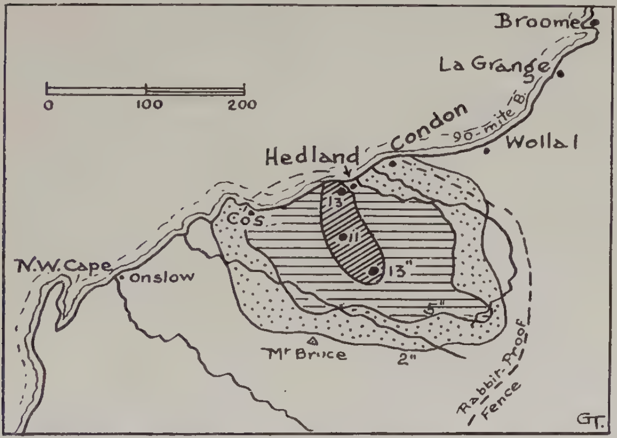

FIG. 179. Heavy rains associated with the *Koombana* hurricane of March 1912. Two-, five-, and ten-inch isohyets shown.

'The hurricane was moving southward, and its centre was not far out to sea, as the *Bullarra* experienced half-an-hour's dead calm (in which it was possible to keep a match alight) in the middle of the hurricane. Officers of the ships *Moira* and *Bullarra* say that the rapidity of the storm was indescribable, the wind driving from the raging and foaming sea spray like a snowstorm, which mingled with the clouds.

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[1] Violent thunderstorm.

'As the *Koombana* left the port, she was so light that her propeller was partly out of the water, and in the small swell at the entrance was racing. Once outside, Captain Allen had no other course open but that which led his ship right into the vortex of the tremendous elemental strife which prevailed at sea.'

CHAPTER XXII

UPPER AIR RESEARCH

Elsewhere the fact has been emphasized that we dwell at the bottom of an ocean of air, whose movements are largely determined by the solar heat impinging on the upper layers. Our records deal almost wholly with the lower 100 feet of this deep ocean, and our knowledge of the main meteorological phenomena is therefore still very meagre.

With the advent of research in the upper air many new facts were brought to light which have totally disproved some old theories, and which are already giving rise to new hypotheses which have proved of great value. In the first chapter it was shown that this study is not yet twenty years old, and dates really from the discoveries of Teisserenc de Bort at the dawn of this century.

I propose in this chapter to commence by describing the procedure as carried out at Melbourne, where numerous soundings were made in 1913 and 1914, before the war cut off our supply of balloons.[1]

Apparatus. The *ballon sonde* is a rubber balloon of about 3-feet diameter, when fully distended with hydrogen. The latter is now obtainable in pressure-cylinders, and is led directly into the balloon by means of a length of rubber tube.

The balloon carries up the meteorograph, an instrument which records pressure and temperature, and which must be very light. The meteorograph enclosed in its protecting cylinder of aluminium is about 8 inches long, and is lashed firmly to a bamboo frame. The latter is called the 'spider', and consists merely of three thin split bamboo strips (all at right angles) which are lashed at their centres, and stayed with threads from their extremities. The spider serves to preserve the instrument from breakage when it reaches the ground. It is adorned with small red flags which make it readily visible on its descent. A parchment label requests the finder to return the meteorograph to the Weather Bureau.

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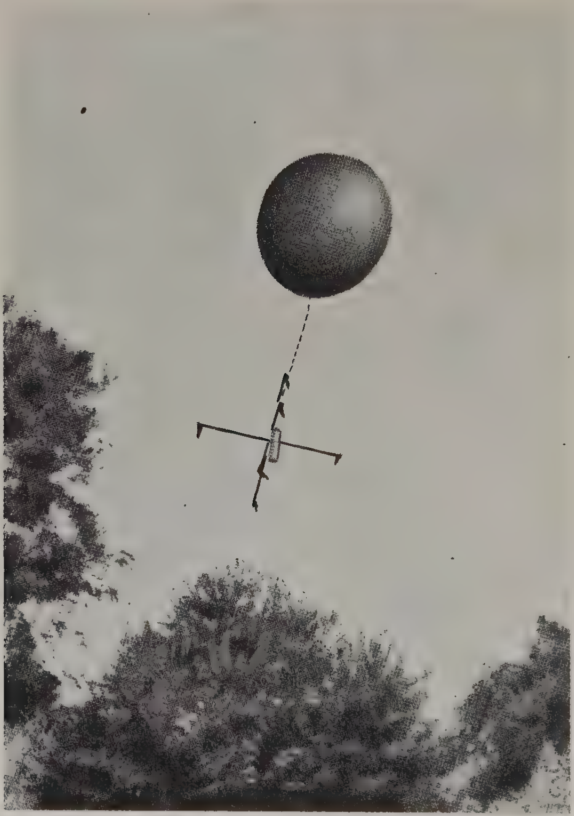
[1] Bulletin 13, by Griffith Taylor, 1915 Melbourne.

The meteorograph usually used by British investigators is that due to W. S. Dines (who also perfected the pressure-tube anemometer). The mechanism is shown in Fig. 181. A single aneroid cell is connected by a bar to a simple two-metal thermograph.



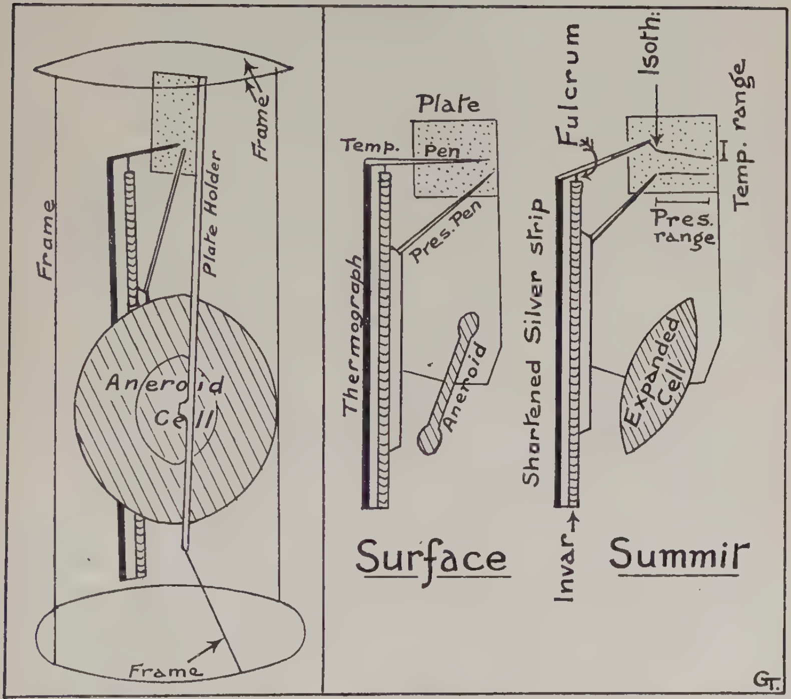
From Met. Bull. 13. *Photo by 'Sun' Newspaper.*

FIG. 180. A balloon ascent, Sydney, 1915. (The balloon is 3 feet across; the meteorograph cylinder is 8 inches long and is attached to the centre of the bamboo spider.)

The latter consists of two parallel strips of metal, the outer German silver, the inner of the alloy 'Invar'. This alloy is almost unaffected by temperature; in fact it is practically invariable, hence the name.

Levers ending in points—and thus acting as pens—are attached to the aneroid and to the thermograph. The whole is stiffened by a wire frame which fits snugly inside the aluminium cylinder. This latter is not shown in the figure.

The action is best understood from Fig. 182. At the surface the aneroid is collapsed by the pressure of the air (as shown in section). The silver strip of the thermograph projects beyond the Invar strip, and the pen ‘ rocks ’ on the fulcrum as shown. The record plate consists of a silvered copper plate about the size of a postage stamp, and is shown dotted in Figs. 181 and 182.



FIGS. 181, 182. Left, sketch of the Dines Meteorograph. Right, diagrams showing the positions of the pens on the record plate at the start and at the summit of a flight. The record is enlarged in Fig. 186.

As the meteorograph is carried up into the air by the balloon, the aneroid cell expands and so the attached thermograph and *both* pens move bodily to the left. Hence both pens scratch lines on the copper plate as the balloon rises. But the silver strip is also shortening, with the result that the temperature pen moves away from the pressure pen. Hence the temperature line runs obliquely to the pressure line, and the lower the temperature experienced the greater the deviation.

When the instrument has reached so high that the balloon has expanded to its limit, the rubber bursts and the whole outfit falls to the ground. The burst balloon acts as a sort of parachute, and so the records are rarely damaged.

On the descent the pens retrace the curves they have made (Fig. 177), or if conditions have changed during the hour or two of their flight the return line will appear close beside the other.

The copper plate is now removed and with a lens two delicate lines can be seen, one recording the air pressure (or height of the flight), and the other is a measure of the temperature. The plate is placed in a microscope and the record is now deciphered.

Calibration. We must now discuss how the plate has been prepared for the record, i.e. how it has been ' calibrated '. Before the ascent the whole meteorograph was placed in petrol in a small receptacle enclosed in a strong wooden jacket. This chamber can be connected to an air-pump, and the jacket can be filled with extremely cold expanding gas from a carbon-dioxide cylinder.

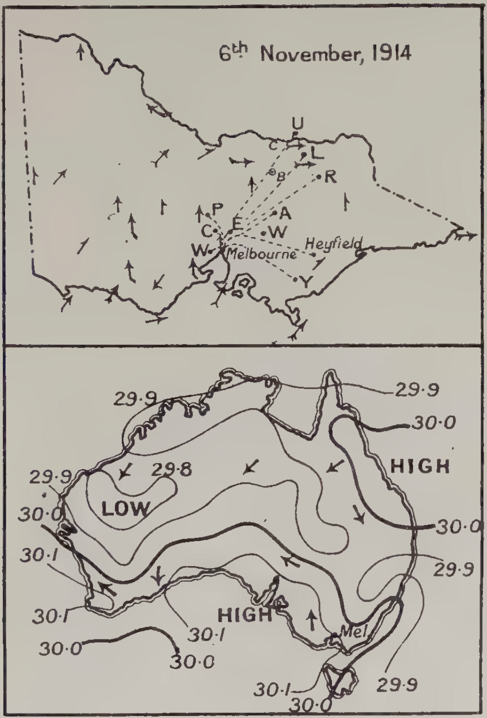
An ingenious electric tapper can be operated inside the hermetically closed chamber, so as to make the pens scratch a mark on the plate at any required pressure or temperature. The plate is therefore subjected to a sort of preliminary test in the laboratory. By reducing the air pressure in the chamber the aneroid is affected as if it had risen to great heights. By reducing the temperature the silver strip is contracted and the pen makes a series of marks at the corresponding temperatures, if the electric tapper is put in action. The following table shows a typical calibration record:

	Instrument 355.		*Room Temp.*	*Barometer.*
Isotherm A.	20 November, 1914,	9.45 a.m.	68·6° F.	30·068
B.		12.20 a.m.	71·5° F.	30·015
C.	24 November, 1914,	10.30 a.m.	68·5° F.	29·972

	Temperature of Petrol.		*Pressure Exhaustion Marks.*				
	Start.	*End.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*
Isotherm A.	18° C.	17·8° C.	300	400	500	600	687
B.	−19° C.	−17° C.	300	399	500	600	722
C.	−62·2° C.	−62° C.	300	400	500	600	722

Before the record plate was sent up, it was therefore marked sufficiently to show four pressure ordinates and three temperature ordinates.[1]

The ascents were made usually about 4 p.m., so that the sun would not heat the thermograph unduly. The flight was watched for about half an hour (as long as the balloon remained in sight) through a Casella self-recording theodolite. This instrument draws two curves showing altitude and azimuth (horizontal angles), and enables one to discuss the variation in wind direction in the lower layer of the atmosphere (see Fig. 185).



Figs. 183, 184. Top, map of Victoria showing various tracks of *ballons sondes* from Melbourne. The winds for the day of the Heyfield flight are shown. Bottom, weather chart for 9 a.m. of the day of the Heyfield flight.

The following account shows the procedure in a typical *ballon sonde* experiment.

An Actual Ascent. On the 6 November, 1914, an instrument was liberated from the grounds of the Melbourne Weather Bureau, and it was returned from Heyfield (see Fig. 183) on the 9 December.

---

[1] In Fig. 186 six such marks are indicated by circles on isotherm −37°.

Weather. The weather at 9 a.m. on this date is shown on Fig. 184. A high-pressure area lies over Adelaide, while the region of the ascent was at a pressure of 30·1, with strong south-west winds blowing on shore from King Island. Owing to the position of the Bureau near the coast, when it is safe to liberate a balloon the normal clear weather conditions are always of this type. The cirrus was from the west.

Theodolite Traces. The ascent was watched by two theodolites, the small instrument acting as a check on the automatic theodolite. Owing to the cramped position of the station the azimuth readings on the small instrument could be taken after the balloon was hidden from the other observer. The chart obtained is shown in Fig. 185. The interpretation of this record involves the use of several approximations as to the vertical and horizontal velocity of the balloon. Dines gives a factor of approximately 200 metres per minute for the ascent of balloons; and we may provisionally adopt this value for our ascents.

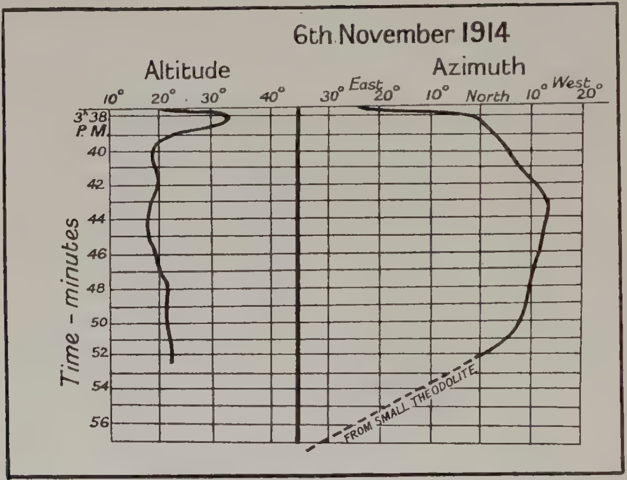


FIG. 185. Self-recording theodolite curves for the Heyfield flight.

Mr. Quayle's observations of the cirrus velocity during November 1914 gives an average value of 94 seconds for the period occupied by the cirrus in travelling across an arc of 15°. (Twelve observations were averaged.) Assuming their height to be 27,000, this gives us a value of about 5,000 feet per minute (1,500 metres per minute) for the balloon when it reaches the cirrus levels (about 8,000 metres up).

Thus we see that it started at 3 hrs. 37 min. 30 secs., and was carried to the north-east for the first minute, but then moved NNW. for a period of nearly ten minutes. It was ascending all this time so that it seemed to float at a constant elevation of 20°. At 3 hrs. 50 mins. it was caught in the westerly winds, and then moved rapidly to the east, being lost to sight at

N. 30° E. about 3 hrs. 57 mins. Assuming Dines's factor it would seem to have entered the westerly drift at 2,800 metres (i.e. in 14 minutes).

Balloon Track. The balloon was not visible for more than eighteen minutes, and thereafter we learn its history from the meteorograph record. It was picked up on the 26 November near Heyfield. This town is in Gippsland, and is between Walhalla and Sale, 100 miles ESE. in a direct line from Melbourne. We may assume that the balloon fell there about 6 p.m. on the 6 November (see Fig. 183).

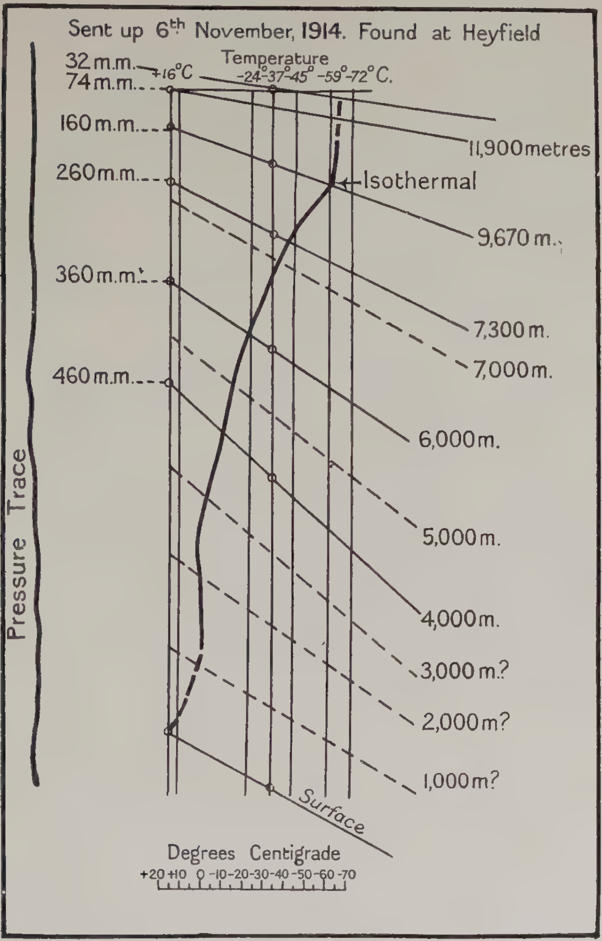


FIG. 186. Meteorograph record; showing that the balloon entered the stratosphere at 9,670 metres, where the conditions became isothermal.

The record is shown somewhat diagrammatically in Fig. 186.

The temperature line exhibits very clearly the critical point where the instrument entered the isothermal layer. The following table shows the results obtained from this flight:

TEMPERATURES OVER MELBOURNE, 6 NOVEMBER, 1914, 4–6 P.M.

11,900 metres	−63° C.
11,000 ,,	−62° C.
10,000 ,,	−60° C.
9,670 ,,	−59° C.
9,000 ,,	−55° C.
8,000 ,,	−46° C.
7,000 ,,	−40° C.
6,000 ,,	−23° C.
5,000 ,,	−14° C.
4,000 ,,	− 9° C.
3,000 ,,	− 0° C.
2,000 ,,	+ 3° C.
1,000 ,,	?
Surface	+16° C.

HEIGHTS OF THE ISOTHERMAL LAYER. The Melbourne records are not numerous enough to show any apparent relation between the season and the height of the isothermal layer. Moreover, too much stress must not be laid on the very imperfect records numbered 5 to 14.

Season.	*Height of Isothermal.*	*Date.*	*No.*
Winter	14 kilometres	4 July, 1913	14
,,	11½ ,,	23 May, 1913	8
,,	11 ,,	10 June, 1913	12
Summer	10 ,,	6 November, 1914	26
Winter	10 ,,	14 May, 1913	5
,,	9½ ,,	6 May, 1914	22
,,	9½ ,,	20 May, 1913	7
Summer	9 ,,	25 February, 1915	31
Winter	8 ,,	20 May, 1914	23
Summer	8 ,,	12 December, 1913	20

From this table we may conclude that the average height of the isothermal layer over Melbourne is 10 kilometres.

To understand the more detailed results which are being obtained from upper-air research it is necessary to refer to the work done at the older bureaux in Britain and America and elsewhere.

BRITISH ASCENTS. Cave has discussed in his book, *The Structure of the Atmosphere in Clear Weather*, the results of some 200 ascents over the south of England. He finds that the balloons travel under the influence of six classes of winds, of which the four following are the chief.

CLASS A—THE SOLID CURRENT. Here the air stream is fairly uniform up to great heights; so that presumably isobaric conditions are somewhat similar throughout. For instance on 5 August, 1909, a balloon ascended to 18 kilometres with a wind velocity hardly rising above 5 metres per second throughout. The direction was north-east at the surface in accord with a High over Denmark;[1] and the wind kept its easterly direction until 12 kilometres was reached.

CLASS B—CONSIDERABLE INCREASE OF VELOCITY WITH HEIGHT. Here the gradient wind is usually reached about 1 kilometre up. On 2 February, 1908, a north wind at the surface of about 8 metres per second increased to 30 metres at 3 kilometres. A High lay to the south of Ireland and the isobars were probably much closer together at the higher levels—as Cave postulates.

CLASS C—DECREASE IN VELOCITY. This is associated often with a High to the north. The surface winds (in the northern hemisphere) are from the east. On 3 March, 1910, such an east wind dropped from 10 metres at the surface to 5 metres at 3 kilometres. It gradually changed in direction to the north at 7 kilometres.

CLASS D—REVERSAL OF WIND DIRECTION. These are often due to the surface control disappearing at a few kilometres up, and then the winds appear to agree with a more distant system. Thus on 21 May, 1907, a south-east wind backed to north-east at about 1 kilometre, and then changed through south to west at 2 kilometres. This was due to the Low over Brittany disappearing at higher levels, where the air was affected by another stronger Low over the North Sea. In some very interesting cases the air supply of a High is indicated by a study of such wind reversals, as on 7 November, 1908.

Various other features are discussed by Cave. Thus he finds that the wind usually diminishes greatly in intensity at about 10 kilometres (i.e. when the stratosphere is reached), though it keeps the same direction. Here also the temperature ceases to fall, as we have noted in the Melbourne records. But this layer where the temperature decrease ceases is not always at the same level; but rises or falls in accord with the somewhat mysterious surges of the troposphere (or lower layer of the atmosphere).

HIGH ALTITUDE WINDS. In a recent paper by Blair[2] he welds together many of the recent results and gives a coherent picture of the wind circulation at very high altitudes (see Fig. 187). For instance, on 9 July, 1914, a balloon rose to 31·6 kilometres from Fort Omaba, Nebraska. At this height there was an easterly wind with a velocity of 19 metres per second (45 miles an hour). In most other ascents in these latitudes an easterly wind was also reached at the 17-kilometre level; between was a layer of westerly winds.

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[1] In Britain the winds blow clockwise around an anticyclone (or High), and anti-clockwise round a cyclone (or Low).

[2] 'Planetary System of Convection', *Monthly Weather Review*, April 1916.

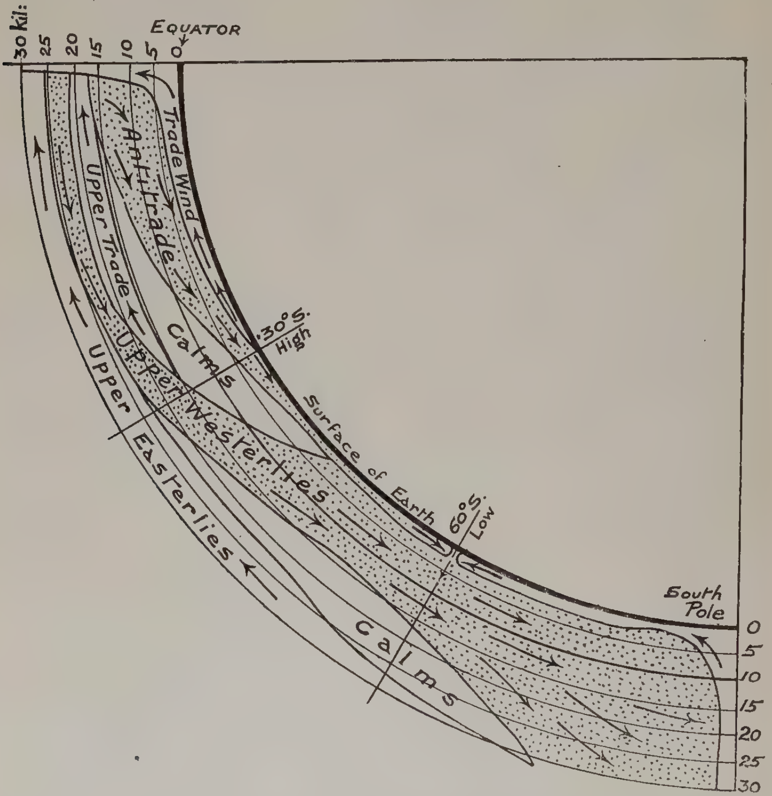

FIG. 187. General circulation of the atmosphere up to 30 kilometres in the southern hemisphere. Westerly wind layers are dotted. (Modified from Blair.)

Over the tropics the upper westerly winds are found at about 20 kilometres above sea level and are approximately 5 kilometres in depth. Above them again the wind is easterly. Below these westerlies are upper trades (easterly); then come the anti-trades (westerly) between 4 and 16 kilometres, and finally the trade winds influencing the lower 4 kilometres of air.

In the polar regions an anticyclonic circulation tends to prevail below the upper westerly wind. The surface easterly winds are shallow, being usually less than 1 kilometre in depth.

Several layers of calm air—or with light variable winds—are shown on the diagram, which in view of the paucity of data is admittedly only a first approximation to the truth.

VELOCITY AND ALTITUDE. Special attention has been given at Rome to the average changes in wind velocity with altitude.

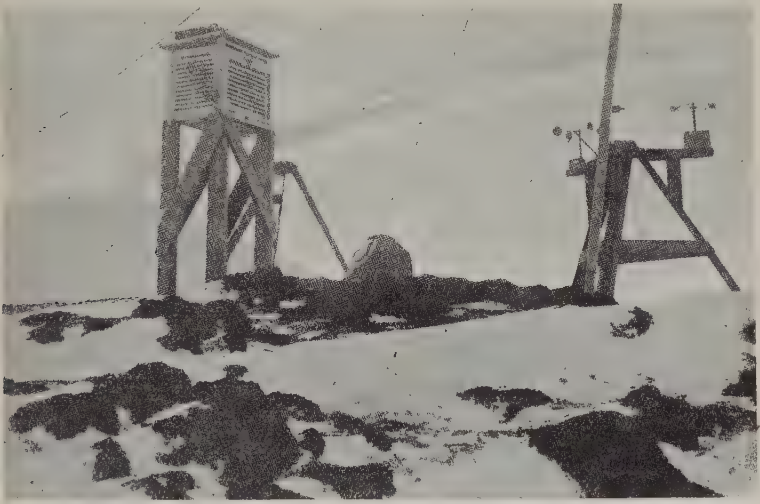

FIG. 188. The screen and anemometers at Cape Evans, Antarctica, 19 September, 1911. Note the steam banner blowing to the south from Mount Erebus.[1] (See Fig. 88.)

In Fig. 189 the results obtained from balloon ascents during 1910 and 1911 are plotted for summer and winter.[2]

The wind velocity is greater throughout in winter up to heights of 5 kilometres. There are three well-marked zones shown in the wind graphs. The lower half kilometre is characterized by a rapid increase of velocity. This is due to the falling off of the friction effect of the earth's surface.

Then comes a layer of variable velocities from a half kilometre up to 2 kilometres. Here is usually considerable mingling of air through convection, and through the various counter-winds which blow in the lower layers of the atmosphere.

---

[1] This photograph is from the writer's book, *With Scott—The Silver Lining* (London, 1916). On pages 305–7 some of the trials of an Antarctic Meteorologist are described.

[2] See *Weather Forecasting in U.S.A.*, p. 36, Washington, 1916.

Above 2 kilometres the velocity rapidly increases with ascent up to 5 kilometres, and thence probably continues to increase up to the isothermal layer at about 10 kilometres.

Probably this graph represents fairly closely the conditions in temperate regions about latitude 35°, and so will serve well for southern Australia.

The Cause of the Isothermal Layer. Few problems in meteorology have proved so difficult as this. Several theories have been published. Milham lays great stress on the warming power of the dust particles in the rare air about 10 kilometres up. Put briefly, he believes that the cosmic dust (which is uniformly distributed through the atmosphere) receives much the same heat from the earth whether it be 2 miles or 10 miles above the earth ; and so is capable of warming the *scattered* air particles at the greater height to a greater degree than the *more numerous* particles at lower elevation. This theory would perhaps explain why the temperature ceases to fall rapidly above 10 kilometres, but is by no means complete.

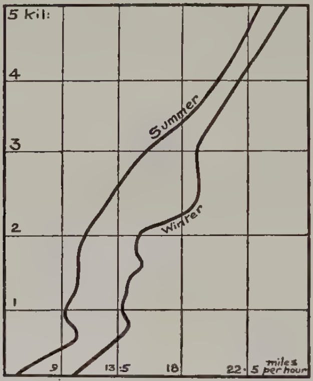

Fig. 189. Mean wind velocities in upper air at Rome during 1910–11 (after Fabris).

But the more striking fact is that the isothermal layer (as shown by the *point of inflection* on the meteorograph trace) fluctuates in position in much the same way as does the outer cloud layer of cirrus. It is lower in winter than in summer. It is lower at the poles than at the equator (see Fig. 47). Hence one is led to believe that this sudden change is due to the blanketing effect of the cloud layer.

If one takes temperatures at varying distances from the stove in a greenhouse, one finds the temperature falling off relatively rapidly (within the house) as one recedes from the stove. A critical point occurs at the glass walls of the house, but outside, there is hardly any decrease for a much greater distance from the stove.

We may compare the warmed earth to the stove, and the moist air up to the outer cloud (or cirrus) layer to the warmed air in the greenhouse. Outside the protecting media there is a sudden change in both examples, and then a very slight decrease in temperature.

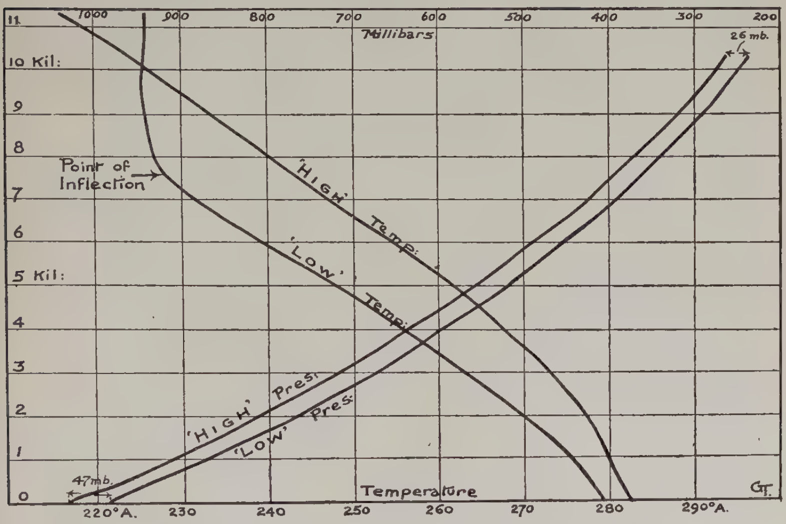

FIG. 190. Upper air values in Highs and Lows for pressure and temperature (means for England, based on Shaw and Dines).

In Fig. 190 are shown some of the main physical results obtained in England for the upper air. We notice that the Low is colder than the High up to 10 kilometres, where they are of equal temperature. The isothermal layer (or stratosphere, as it should properly be called) is much lower over the Low than over the High, as has been indicated in the chapter on the ‘ Structure of the Low ’ (q.v.).

The pressure differences are also shown on the same diagram. The High is seen to differ more from the Low at the surface than at 10 kilometres, the figures being 47 millibars and 26 millibars respectively.

The leading meteorologists are coming more and more to the conclusion that it is to the upper air we must look for the key to all our problems. Sir Napier Shaw writes :

> ‘ We feel that the motion of the air in the lowest kilometre had better be disregarded or better still be handed over to students of turbulent motion, while we as meteorologists consider the normal state of the atmosphere as motion under balanced forces.
>
> ‘ We should regard the troposphere as a layer of about 9 kilometres thick always striving to arrange its motion according to balanced pressures [i.e. gradient effects and Ferrel effects] and perpetually baffled in its endeavours by the ubiquity of convection.’

In another chapter are mentioned some of the remarkable relations existing between conditions at the isothermal layer (limiting the troposphere) and those in the air beneath. This line of research is only a few years old and cannot further be dwelt on in these pages ; yet it is certain that meteorology will reach her rightful place among the sciences when the new and powerful weapon of upper air research is fully perfected.

CHAPTER XXIII

FORECASTING

'*A modern meteorologist thinks in maps*' (Shaw).

Value and Preparation of Charts. It is sometimes difficult to convince the layman that the data on the weather maps are a much better guide to the forthcoming weather than the mere look of the sky. If the onlooker were in the position to see the meteorological phenomena over a whole continent at a glance, he would obviously be in a very favourable position to predict the weather—but this (as has been pointed out) is what the weather map does for the forecaster.

> 'The more expert and accomplished the meteorologist, the more certain he is that all he can do, without the materials for constructing the map (though he may have a barometer and other instruments at hand), is to make a guess at what the map is like—and think out, from that, what the weather changes are likely to be.'[1]

Hence the weather bureaux are dependent for the forecast data on an army of observers, whose figures are telegraphed in time for the noon forecast to the State and Central Bureaux.

The great majority of observers are in charge of rain-recording or fourth-order stations. These send in usually a monthly sheet.

There are, however, many stations which send in a daily record by telegraph, and these range from second to fourth-order stations.

Approximate Classification of Stations

First order	Self-recording apparatus. Three or more readings a day.
Second order	Barometer. Four thermometers, &c. Two readings a day.
Third order	Usually max. and min. thermometers and rain-gauge. One reading a day.
Fourth order	Usually rain-gauge only. One reading a day.

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[1] *The Weather Map*, by Napier Shaw, London, 1916.

Climatological stations are usually second-order stations, but there are also numerous third-order stations in this class. Their total in the Commonwealth is about 220.

The Commonwealth Weather Service is organized somewhat as follows:

COMMONWEALTH METEOROLOGIST

Central Bureau, Melbourne.
10 Professional Officers
34 Clerical Officers
1042 Observers in Victoria

Other States.

New South Wales.	*Queensland.*	*S. Australia.*	*W. Australia.*	*Tasmania.*
2 Professional	1 Professional	1 Professional	1 Professional	1 Professional
5 Clerical	5 Clerical	5 Clerical	5 Clerical	2 Clerical
2043 Observers	1003 Observers	654 Observers	981 Observers	255 Observers

THE PROCEDURE IN FORECASTING. At 9 a.m. (local Victorian time) some 2,000 observers are reading their instruments all over Australia. These records are telegraphed by code to the bureaux at the state capitals. Thus Sydney receives 606 telegrams, including about 120 from neighbouring states; while the head bureau at Melbourne receives 300, equally divided between Victoria and stations beyond Victoria.

These records are tabulated and then plotted on large maps, which show pressure, pressure variation, temperature, rain, cloud, storms, and other features graphically. These charts are usually ready at noon, and are studied by the Commonwealth Meteorologist and the other forecasters.

The resultant forecasts for Victoria and the other five states are immediately telegraphed to the respective centres for publication.

They are communicated to the papers and large numbers of cyclostyled maps and tabular statements are posted in prominent buildings, &c. A system of warning flags is in operation and special storm warnings are sent to signal stations and other localities likely to be interested.

MAJOR PRINCIPLES OF FORECASTING. As regards the greater number of weather charts, the general character of the charts for the first and second successive days can be forecasted if the principles embodied in earlier sections of the present work are intelligently applied. It is the less usual occurrences which of course demand the skill of the experienced forecaster, and no brief description will enable the student to cope with them.

These major principles may be recapitulated as follows :

A. There is a definite relation between the weather at a place and its position with regard to the pressure system, whether Highs or Lows.

B. These pressure systems move to the east at a more or less uniform rate of about 500 miles a day, and as it were carry the appropriate weather over the locality under examination.

C. The paths of the systems vary with the season—moving north and south with the sun.

D. The paths of the tropical Lows (south of latitude 20°) are usually to the south-east rather than to the east ; moreover these Lows have a tendency to hover over a place, especially if their intensity is slight.

E. The behaviour of the Lows is always more erratic than that of the Highs, and correspondingly more difficult to forecast.

F. The chief disturber of normal conditions is perhaps the east coast Low, which seems to 'hold up' all movement over the mainland until the Low has disappeared to the east.

G. The vicinity of seas or mountains exerts a considerable modifying effect on the pressure systems, especially as regards rainfall and temperature.

EXAMPLE OF MOVEMENT OF EDDIES. The passage of Highs and Lows is illustrated in Fig. 191. Here is a weather 'belt' consisting of two Highs with a Low between. The axis of the Highs is about the latitude of Adelaide (35° S.). We should, therefore, expect the chart to belong to spring or autumn (see Fig, 58), and, indeed, it is based on charts for March 1915.

On the 9th south-west winds with some coastal showers were experienced at Melbourne (Fig. 191). The High extends westward over the Bight. It is obvious that no great change is imminent, or some other control would be apparent near Adelaide. We will therefore make a forecast for *two days* later.

The High will have moved about 1,000 miles to the east in that time, giving the effect shown for the 11th of March in Fig. 191. This brings Melbourne right into the middle of the High. We should expect calms, clear skies, dews, and frost in the highlands, and that is just what occurred.

By this time a Low was apparent south of West Australia. If we are to forecast for the 13th of March we must move the High and Low another thousand miles to the east for their two days' travel. Northerly winds will be experienced and probably some rain.

The amount of wind and rain is closely connected with the intensity of the oncoming Low. If the latter shows numerous isobars and low pressures (below 29·7 inches) at the centre, then the northerly winds will be more definitely developed and the rain may be heavy. As the centre passes a pronounced wind-shift may occur from north to south-west.

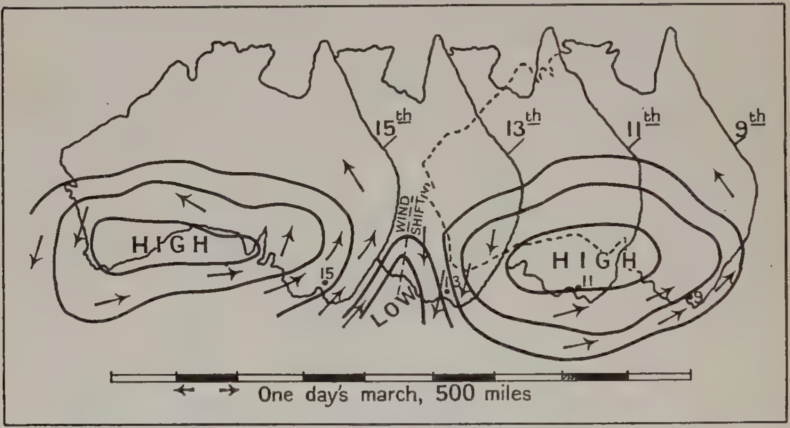

FIG. 191. Diagram illustrating a daily movement of the weather controls about 500 miles to the east in each 24 hours. Alternate days (in March 1915) are charted by imagining the continent moved (in a contrary direction) under the continuous weather controls in four stages of 1,000 miles each.

If the approaching Low is feeble with a gentle gradient the winds may be somewhat variable, and rain is less likely. The latter conditions obtained on the 13th, and there were only showers as a result (Fig. 191 for 13 March).

With a further march of one thousand miles to the east the next High will have advanced to Melbourne by the 15th, giving a chart which is almost the same as that for the 9th of March. Hence a High takes about six days to traverse Australia. Similarly we can readily understand that if a Low dominates Victoria at one week-end, there will quite probably be another over Melbourne in a week's time. Hence there is a scientific basis for the schoolboys' belief that a wet week-end means wet Saturdays for some time to come!

Thus the golden rule in Australian forecasting is as follows: *The weather types move* 500 *miles to the east every twenty-four hours.*

When the pressure controls are erratic, moving more rapidly or more slowly than usual, or when their tracks are oblique or even worse, retrograde, it is impossible to give general rules.

'Habit'. The question of 'habit' is of importance. In some seasons the isobars will have a persistent shape for weeks at a time. For instance, the winter of 1914 (June, July, and August) was characterized by an almost unbroken series of huge oval Highs which hovered over the continent and materially affected the winter rain supply. Shaw makes a pertinent comment on this 'irrationality of inanimate things'.

> 'After a dry period the weather sometimes seems unable to rain even under barometric conditions which are apparently most favourable for it. The peculiar "mood" or "fit" of the weather is a great difficulty for the forecaster.'

Many such examples of isobaric habit have been noted in my study of rain origins in *Australian Environment*.[1]

PRESSURE SYSTEMS ASSOCIATED WITH RAIN

Type of Low.	1910.	1911.	1912.	1913.	1914.
North-west Australia, *Coastal Lows*	Common	Few	Common	Common	Few
Central West Australia, *Tropical Lows*	Few	Few	Few	Common	Common
Swanland, *Antarctics*	Common	Few	Few	Common	Few
Central North Territory, *Troughs*	Few	Few	Common	Common	Common
Adelaide region, *Tongue-Tip Cyclones*	Few	Few	Common	Common	Few
Queensland, *Coastal Lows*	Common	Few	Few	Common	Common
Victoria, *Antarctics*	Common	Few	Few	Common	Few

It therefore behoves the forecaster to keep this factor in mind, and to note if any seasonal idiosyncrasy is making itself apparent.

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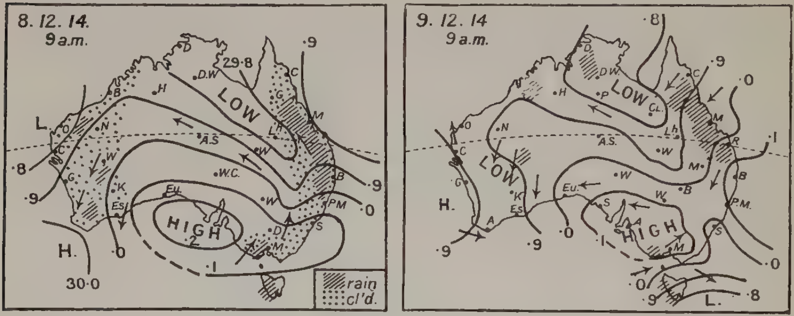
[1] Published, November 1918, by the Commonwealth Advisory Council of Science and Industry, Melbourne (p. 188, fig. 183, Quarto).

Example of Forecasting. An actual example of forecasting will make the matter more intelligible to the student.

For 8 December, 1914, the weather chart is given in Fig. 192. A High dominated the south of Australia, while the low-pressure isobars formed the two usual summer loops near Cloncurry and Pilbarra.



Figs. 192, 193. Practice in forecasting, based on two charts in December 1914.

Weather Conditions (sent by telegraph)

	Victoria.	*South Australia.*	*New South Wales.*
At 9 a.m. on the 8th.	Clear in north, otherwise cloudy to overcast. Showers on south-west coast.	Cloudy to overcast on coast. Elsewhere clearer.	Cloudy to overcast on coast and tablelands; light rain on Blue Mountains and north coast. Clear inland.
For the previous 24 hours (i.e. 7th March chiefly).	Light rain on west coast.	No rain.	Light rain on north coast and Blue Mountains.

	Tasmania.	*Queensland.*	*West Australia.*
At 9 a.m. on the 8th.	Cloudy to overcast throughout; some misty rain.	Cloudy to gloomy on coast and Darling Downs. Elsewhere clear.	Clear to cloudy on south coast and in tropics. Cloudy on goldfields. Elsewhere clear.
For the previous 24 hours (i.e. 7th March chiefly).	Light rain at few scattered places.	Light to heavy rain in eastern littoral and highlands.	Light rains through goldfields.

FORECAST FOR NEXT TWENTY-FOUR HOURS (TILL NOON OF 9TH)

State.	*Forecast.*	*Reasons.*
Victoria.	Fine except showers on coast.	Centre of High approaches with dry descending air, but onshore winds may give a few showers as before.
	South-west to south-east winds, later light and variable.	Within twenty-four hours the calm region of the High will cover Victoria.
	Seas smooth.	Owing to gentle gradient of isobars.
New South Wales.	Generally fine except north coast.	The south-east winds in front of High are onshore winds on north coast, and the clouds there indicate moisture. Temperatures and winds will not change materially.
South Australia.	Generally fine, variable winds becoming more northerly with rising temperature.	The usual consequences of the passage of the centre of the High to the east.
Queensland.	Further coastal rains. Fine inland.	The cloud shows humidity, and the onshore winds are favourable for rain on the coast. The inland loop is not intense enough for much rain development inland.
Tasmania.	Generally cloudy, more showers in west and south.	Controls remain much the same, therefore the weather will not change.
West Australia.	Cloudy in west, clear inland. Few scattered showers. Warmer.	The Low will probably move inland to the south-east as usual. This will increase the coastal cloud and cause more showers but no heavy rain, as control is too weak. Thunder probable in warmer regions as convection strong. The temperature will become warmer as north winds strengthen with movement of Low.

The chart shown in Fig. 193 verified these forecasts.

BRIEF NOTES ON FORECASTING VARIOUS PHENOMENA

PREDICTION OF STORMS. These may be divided into the two groups, Gales and Hurricanes. The former arise when the gradient of the Low is very steep, and are common along the south and south-east coasts when Antarctics are numerous, i.e. in winter. They also occur with similar charts at other seasons.

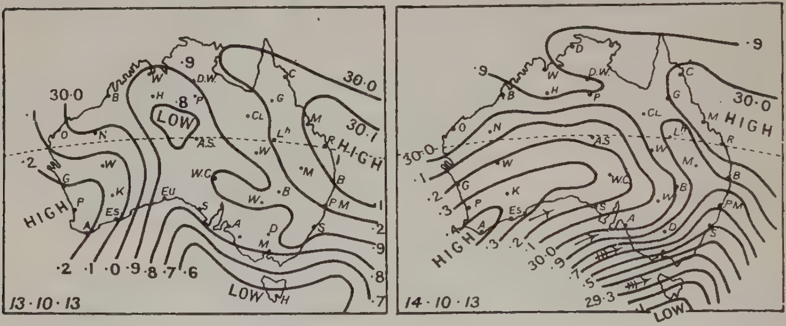
In October 1913 a well-developed Low occupied the Bight on the 13th, and it moved normally to the east with intensifying gradients. On the 14th the gradient steepened greatly over the Bight (as shown in Fig. 194), the isobars from 30·2 to 29·6 being closely packed together. The forecast was as follows :

‘ Squally winds and rough seas east from the Bight.’

This was abundantly verified, as Fig. 195 shows ; for on the 15th a severe storm swept Bass Straits and the barometer fell to 29·2 at Hobart ; while the wind rose to 69 miles an hour at Melbourne.

It is necessary to consider the aspect of the coast in connexion with ocean warnings. Thus a south-west wind has much less effect on the New South Wales coast than on the Victorian coasts.

Prediction of Hurricanes. These are luckily limited in season and locality. Their characters have been discussed in an earlier chapter. In the warm months the forecaster is suspicious of every low pressure approaching the tropics from the north-east ; and if it appears to be associated with a circular system of isobars it is quite probable that it will develop into a hurricane as it reaches the danger zones. The barometer, the peculiar ocean swell, and the direction of the winds are all of great value in forecasting such storms.



Figs. 194, 195. Charts illustrating forecasting for gales in Bass Straits.

Prediction of Thunderstorms. These depend on local conditions very largely, so that it is almost impossible to predict them accurately. But they are commonest when convection is general, and the weather associated with the latter is well known. The front of a low-pressure system, especially its northern side where warm currents of air are flowing into the Low, is a usual position. If the gradient is not well defined so that the air is turbulent (rather than swept in one uniform direction) conditions are most favourable. Abbe states that it is wiser to make no predictions until one or more have occurred in some adjacent region.

Prediction of Rain. This is closely bound up with the study of advancing Lows, and this aspect of the problem is considered fairly completely in Chapter XIX.

But there are other indications apart from the pressure distribution which are found of value. Mr. E. T. Quayle has investigated the relation of cirrus clouds to ensuing rainfall, and has formulated the following rules for Victorian forecasting.[1] They depend on the fact that most of our inland rain is derived from the warm moist inflow from the tropics, and a large supply of moisture is indicated when the cirrus is moving from the north.

(1) If the first cirrus before the approaching Low is from the south-west the rain will be small.

(2) If the cirrus veers to the north as the Low approaches (from the west) then a general rain is indicated.

(3) Cirrus movement persisting from some northerly point in spite of locally fine weather is a very reliable sign of rain.

(4) Cirrus coming from a southerly direction may have no apparent relation to storm systems. It is always an unfavourable sign.

(5) The failure of cirrus to herald the approach of a storm is usually a sign of poor rain-production over inland areas.

Guilbert's Rules for the movement of the Lows[2] have been much used in Europe, but data in Australia are perhaps hardly detailed enough for their application. His rules depend largely on whether the wind at a place is appropriate to the gradient or not. The chief rules are as follows :

(1) A depression (Low) with winds above normal strength on all sides will sooner or later fill up. One with winds below normal will become deeper and may turn into a cyclonic storm.

(2) Those parts of a depression in which the winds are below normal indicate directions in which the depression may advance.

(3) If the winds are *divergent* from the low-pressure area they indicate the approach of the Low.

Obviously the *normal* winds need careful classification, and the isobars must be very carefully drafted before these rules can be used.

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[1] *Meteorological Bulletin*, No. 10, issued May 1915, Melbourne.

[2] See *Forecasting*, by Napier Shaw, London, 1911, p. 319.

Bowie has investigated the relation of the movement of the Low to the pressure gradient in the United States. He studies how the gradient acts on the Low in question from the eight points of the compass. The gradient will be found to be lower in one direction, and the Low will move in a path compounded of this direction and the general drift of the atmosphere.[1]

Prediction of Floods. The general considerations affecting rain hold good for flood prediction also. In general, however, floods are much more likely to occur with rains after the ground is well soaked than when they follow a dry spell. A thorough knowledge of the topography of a river valley which is subject to floods is also necessary. In most of the settled portions of our main river valleys a system of flood warnings is now in operation.

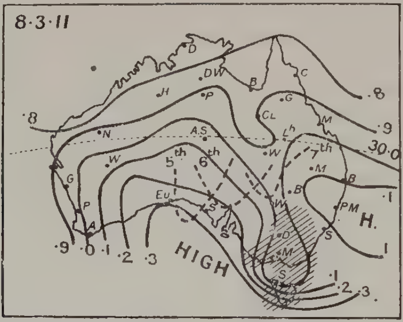

Fig. 196. Flood rains in Tasmania. Previous positions of the tropical tongue are shown by broken lines.

The weather charts for a flood rain nearly always show a strong tropical loop, or trough as the dominant system. Several such rains are described in *Climate and Weather of Australia*, to which the reader is referred for special details.

A very complete account of flood rains in Tasmania is given by Colonel Legge in the Australian *Monthly Weather Report* for March 1911. Eighteen inches of rain fell in places on the north-east coast, and all the rivers were heavily flooded.

The chart shows a narrow tropical tongue penetrating right to Tasmania (see Fig. 196). The preceding chart on the 5th showed a tropical tongue over Eucla, which moved east on the 6th and 7th (as shown) in company with an Antarctic. Early on the 8th a sort of 'tongue-tip' cyclone developed over the Bass Straits from a union of the two low-pressure areas. The rain was, however, confined to the southern areas of the Commonwealth.

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[1] U.S.A. *Monthly Weather Review*, February 1906.

Prediction of Frosts. This is a matter of much less interest in Australia than in most other countries with weather services. The frost map (Fig. 105) will have shown that settlement is scanty where frosts are prevalent.

Frosts are to be expected during the cooler months when an anticyclonic centre is approaching a place. The clear sky promotes intense radiation and chilling of the ground surface, for reasons stated in Chapter XII. The direction and velocity of the wind are also factors to be considered.

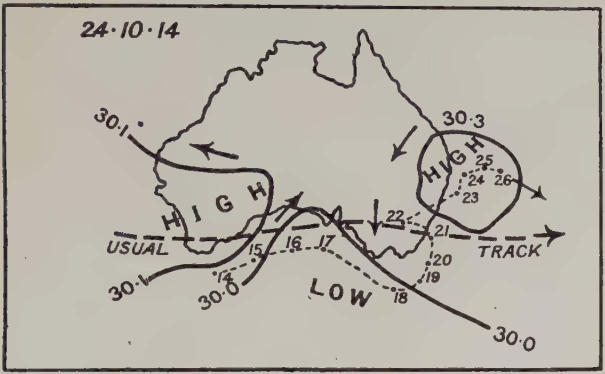

Fig. 197. Chart illustrating a spring heat wave in Melbourne. The heavy broken line is the usual track of the centres of the Highs for seven days in October. The dotted line is the 12-day track of the sluggish High causing the heat wave, showing position of its centre on the dates given.

Prediction of Heat Waves. These are of more interest to Australians than the preceding class of weather. All the heat waves in the south-east of the continent are associated with the northerly winds at the rear of a High. If the anticyclone is stagnant or slow-moving, the hot north winds may continue for days.

A typical heat wave which occurred in October 1914 is illustrated in Fig. 39. The gradual accumulation of heat in spite of the drop in temperature each night is well marked, the midday maximum rising day by day until the 24th.

The charts associated with this heat wave are epitomized in Fig. 197. The centre of the High was south of Albany on the 14th, and then moved normally about 500 miles east each day to the 19th. On the 20th and 21st, instead of continuing to the east, it moved north; and on the 22nd it actually retreated to the west—a most unusual direction. On the 23rd and 24th it had hardly made any easting.

All this time hot northerly winds swept over Melbourne, the temperature reaching 98·4° on the 24th at 3 p.m.—a record for October. In the night the low-pressure trough advanced so far that the wind-shift occurred early on the 25th; and a drop of 20° from the previous morning readings occurred (see Fig. 39) as a result of the southerly change.

The cause of this delay in the passage of the High may be found in the presence of a strong Low far to the north-east of Queensland. However, this is only surmise, though such a depression was indicated by the isobars off Queensland early in the heat wave.

Regions where Forecasting is Difficult. Forecasting for rain is by far the chief problem confronting the forecaster in Australia. It is fairly obvious that the difficulty varies with place and season. For instance, in winter the chances of rain at Darwin are *nil*; and in summer the chances at Perth are almost negligible. On the other hand, in the south-east of the continent rain is frequent in every month and the forecaster has no ‘ off season ’.

Speaking generally the difficulty of forecasting varies with the number of rain-days in the year. In Fig. 198 the variation in this element is plotted, and is seen to agree fairly well with the annual isohyets (see Fig. 120). Thus the regions with more than 30 inches a year need about 100 rain-days for their supply—except on the north coast. Here 60 rain-days in the Territory are approximately equal to 150 rain-days in Victoria, which indicates the heavy nature of the tropical rainfall.

It is of interest to note that Birdsville (Q.) has only 14 rain-days; Hervey Creek (Q.) has 130, and Zeehan (Tas.) 243 in the year.

We may, however, get nearer the true scale of ‘ forecast difficulty ’ by combining Fig. 198 with Fig. 127. In the latter the wet months are charted by isopleths. The result is shown in

Fig. 199. Here the number of rain-days at a place is multiplied by the number of days in the wet season (as shown by Fig. 127).[1] Thus Darwin has 99 rain-days and its wet season is 210 days (7 months); the result is the figure 20,800. Melbourne has 150 rain-days which may occur throughout 365 days, which gives 55,000 as the product. These figures are plotted as 20 and 55 on Fig. 199, and now the forecasting relation between Darwin and Melbourne is shown more exactly.

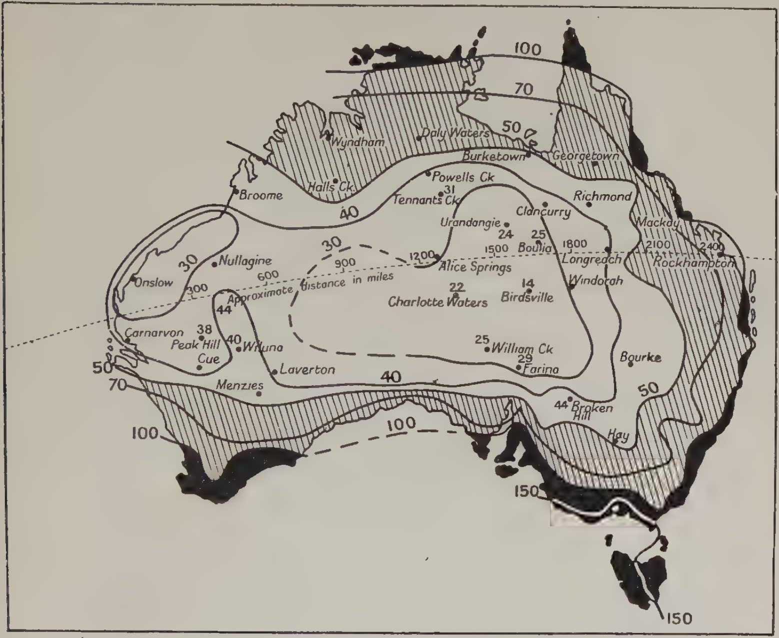

Fig. 198. Number of rain-days in a year.

It is not suggested that these two factors by any means exhaust the difficulties in forecasting, nor that the resulting isopleths in Fig. 199 are quantitatively correct. But they give a closer approximation to the truth than does Fig. 198 alone. The map clearly indicates that Melbourne is the most difficult of the settled districts from the forecaster's point of view. Then comes Sydney, then Brisbane and Hobart; while the weather at Adelaide is easier to judge. Perth is more difficult than appears, because the Lows arrive without much warning from the Indian Ocean.

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[1] Possibly Fig. 126 would serve better.

The arid interior is obviously a forecaster's paradise! At Birdsville (in south-west Queensland) the forecaster could predict fine weather every day of the year and only be wrong four times in a hundred!

Much might be written regarding popular beliefs in the movements of animals as denoting weather changes. But no serious student of meteorology has ever found such indications of any real value. Animals react to *present* conditions, not to future changes—in other words, they merely behave like thermographs or hygrographs, and are much less reliable than their mechanical equivalents.

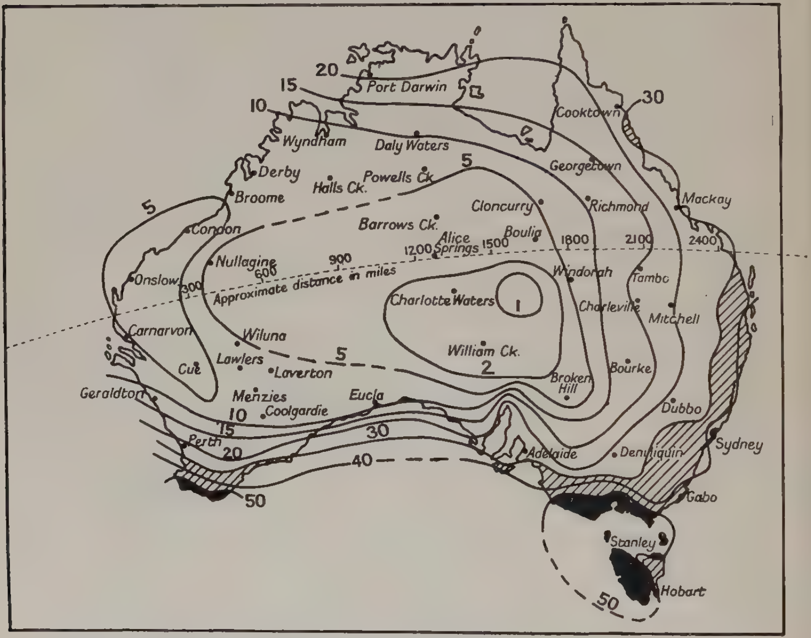

FIG. 199. Grades of difficulty in forecasting rain. The figures ($\times 10^3$) are the product of the average number of rain-days and the length of the wet season. Other factors are ignored. Black areas imply most difficult regions for forecasts.

CHAPTER XXIV

WEATHER CYCLES AND LONG-RANGE FORECASTING

Difficulties of the Problem. It is obvious that the longer the period of the forecast the more valuable it will be—whether to the farmer, soldier, sailor, or man in the street. So far most forecasts in temperate regions are limited to two or three days, while twenty-four hours is the usual period. For meteorologists to be able to make seasonal forecasts it is almost essential that there should be a regular cycle in the character of the weather changes.

Many able investigators have attacked this problem, with the result that there really appears to be a recurrence of the same kind of seasons at intervals of eleven years and of thirty-five years. The former is the sunspot cycle, the latter is Bruckner's cycle.[1] There are also many pseudo-scientific writers who claim to be able to forecast by a study of the planets, of the moon, of magnetic storms, &c., &c. These latter find believers in every continent—chiefly by their insistence on the (infrequent) verifications of their prophecies and by their discreet silence as to their mistakes.

It should be obvious that only the *broadest averages* for large regions should be used in verification of such coincidences, or at least those from stations not subject to great variation during the year (e. g. Powell's Creek, N.T.). Even in a small country like the British Isles, a reference to *Symons's Magazine* for the period 1866–94 shows that there were only three years when exceptional ‘ great rains ’ were not described from at least one district.

Professor Garriott in 1904 wrote the following description, which will be applicable for many years yet, in fact for as long as a non-scientific public retains its love of the marvellous :

> ‘ There is another long-range weather forecaster who draws his support from the American public. His statements are based upon a consideration

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[1] Bruckner's cycles for rain and heat are given as follows by Hann :

Wet .	1736–55	———	1771–80	———	1806–25	———	1841–55	———	1871–85
Dry .	———	1756–70	———	1781–1805	———	1826–40	———	1856–70	———
Cold .	1736–45	———	1756–90	———	1806–20	———	1836–50	———	1871–85
Warm	———	1746–55	———	1791–1805	———	1821–35	———	1851–70	———

of the moon's path, the phases of the moon, disturbing causes due to the movements and positions of the planets, &c.; in fact, a conglomerate gathering of all imaginary and obsolete notions regarding weather causes that are calculated to mystify credulous and uninformed people.

'He predicts the general character of a month with a consciousness that the forecast will be verified in at least some part of a great unspecified area. He then outlines "storm periods" with intervals of two or three days, which are covered by a margin that is claimed for verification purposes, and verifications are claimed if storms occur during the periods or in the intervals in any part of the United States and at times in the northern hemisphere. This system of forecasts and verifications admits of no failures.'

How easy it is for a charlatan to claim such verifications is seen from the following table dealing with the variation of rainfall in New South Wales alone. It bears out the statement that not even in one State is a universal shortage of rain probable, while such a misfortune has seldom devastated a whole climatic region:

WET AND DRY REGIONS IN NEW SOUTH WALES

Date.	*Above Average.*	*Below Average.*
1903	Trans-Darling. New England. Northern Rivers. Blue Mountains.	Western Plains. Riverina.
1904	North-west Slopes. Hunter Valley. Illawarra.	Trans-Darling. Northern Rivers. Southern Tableland. Western Plains.
1905	Western Plains Kosciusko Area.	North-West Slopes. Trans-Darling. Other Highlands and coast.
1906	Trans-Darling. Western Plains. Riverina, &c. Kosciusko.	Other Highlands and coast.
1907	Northern Plains. North-west Slopes.	Trans-Darling. Western Plains. Highlands and coast.
1908	North Coast and north-east generally.	Remainder of state.
1909	Highlands and Western Slopes.	Far West. Western Plains. Coastal Regions.
1910	Far West. West Riverina. North-west Slopes. Blue Mountains.	Western Plains. North Coast. Hunter and Macquarie.
1911	Whole state except north-east.	North-west Slopes. North Coast.

Let us now see the lines of investigation employed by scientists. We may ignore the action of the moon, for this has been shown to produce an atmospheric tide of only 0·11 millimetre even at the equator. This is one seven-thousandth part of the standard atmospheric pressure, and this lunar effect is barely perceptible away from the equatorial regions. The planets can exert no effect whatever.

SUNSPOT EFFECT. By far the most hopeful factor in long-range forecasting was indicated when the variation in spots appearing on the sun's surface was first plotted (see Fig. 203). A sequence of maxima some eleven years apart was discovered, and it was soon shown that these had a close relationship with magnetic storms on the earth. No close connexion with meteorological phenomena has yet been made out. Moreover, the sunspot maxima are sometimes only nine years apart, and again thirteen years, so that the forecaster who uses this system has admittedly a possible error of four years to start with. Great things were hoped from this eleven-year cycle, and much patient correlation was carried out in many centres, notably in India and U.S.A.

One great difficulty in this correlation has lately been overcome. It has been found that when there is a sunspot maximum an increase of solar heat is set free, but apparently the world temperature as a whole is thereby diminished !

Humphreys, in a recent paper, explains the views of his school of meteorology as to this paradox somewhat as follows :

When the sun is active it somehow causes changes in our upper atmosphere. Thus the distribution of atmospheric pressure is disturbed, the strength of the winds is increased ; and the location, area, and relative intensity of the Highs and Lows is altered.

This causes changes in the whole wind circulation, so that corresponding changes in temperature occur. The effect may be an actual reversal of temperature so far as the lower air is concerned.

Thus Veeder suggested that when the sunspots are active much of the cool upper air descends into the major centres of high pressure—and so the lower air is on the whole cooled.

Humphreys believes that the converse is also true ; namely, that the cyclonic centres are intensified and thereby carry the warmer air up away from the surface. Thus again the surface layer of air is on the whole cooled.

CYCLES IN AUSTRALIA. It is difficult to test these views in Australia. As regards the Bruckner cycle (of thirty-five years) we have only one or two stations whose records extend through two such cycles (i.e. seventy years), so that we have too little data for discussion.

It may be noted that one of the worst droughts experienced in Australia was that of 1888. The next big droughts were in 1902 and 1914. The average difference between the successive droughts is thirteen years, which does not fit into any of the cycles. Moreover, 1887 and 1889 were very good seasons, and there was no indication—by a gradual diminution of rainfall to a minimum, such as the theory of cycles demands—that the year between would have a rainfall almost the lowest on record.

It has been stated, moreover, not only that (*a*) coastal and continental regions have opposite weather cycles; but that (*b*) northern and southern hemispheres have opposite weather cycles. Obviously these statements leave wide margins for justification by the long-range forecaster. Moreover, one 'prophet' states that a minimum in the sunspot phenomena implies drought in the southern hemisphere.

Statistics are simple matters to juggle with. Let us, however, choose one of the simplest rain regions in the world, that of Northern Territory, where almost all the rainfall occurs in the summer months and is due to the swing south of the sun (and accompanying air circulation) at that period. We have records for thirty years—extending over three sunspot cycles. Taking Powell's Creek and tabulating the relation of dry seasons and sunspot variations (here the rainfall, October to March inclusive, is used):

RAIN		SUNSPOT	
Wet Years.	*Dry Years.*	*Maxima.*	*Minima.*
Summer of			
1876–7 (large)			1876–7
	1877–8		1878
1880–81			
1882–83 (small)		1882–3–4	
1886–87			1886–7
	1891–2–3 (V. Low)	1892	
1893–4–5 (large)		1893–4	
1898–9			1899–1900
	1899–1900		
1900–1			1901
	1901–2		
1903–4			
	1905–6 (V. Low)	1905–6	
1906–7			
	1908–9		
1909–10			

Considering this table, we see that the first dry summer coincides with a minimum, the second with a maximum, the third with a minimum, and the fourth coincidence was at a maximum.

Hence the relation is not at all simple—and naturally various other factors enter into the problem also.

THE STUDY OF THE CENTRES OF ACTION. Recent research seems to show that abnormal conditions in one hemisphere are intertwined not only with simultaneous, but in many cases subsequent, features in the other half of the earth. The relation that exists between the sequence of weather at one place with the weather following at another place (e.g. Chili and Egypt) is one that has received increasing attention at the hands of meteorologists. It is based on a consideration of variations in the so-called 'Centres of Action'. These are permanent pressure systems, which, owing to a favourable distribution of land and

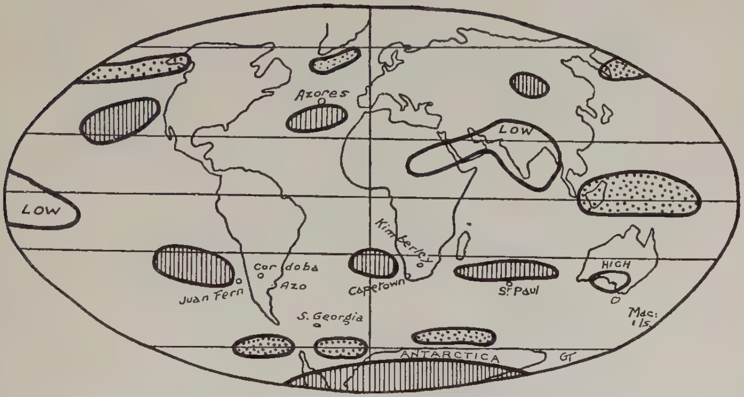

FIG. 200. World 'Action Centres'. More important high pressures ruled. More important low pressures dotted.

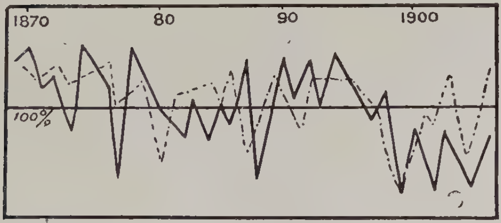

FIG. 201. The relation of the Nile floods (heavy line) to the Chili droughts (broken line). (After Mossman.)

sea, remain more or less over the same areas all the year round: The more important are

(1) the Iceland Low;
(2) the Alaskan Low;
(3) the Indian Low;
(4) the Antarctic Circle Low;
(5) the Siberian High; and
(6) the South Polar High.

There are other less permanent but important Highs usually covering or near (*a*) San Francisco; (*b*) Azores; (*c*) Juan Fernandez; (*d*) Cape Town; (*e*) St. Paul (80° E.); and (*f*) Adelaide (see Fig. 200).

In *Symons's Magazine* for February 1913 R. C. Mossman shows that the Nile floods are high when Chilian rainfall is low, and vice versa. This opposition is exact in the years 1871–1906 for 66 per cent. of cases. The two centres of activity involved are the Chilian High and the Indian Low (see Fig. 201).

The winter rainfall in Chili depends on the position of the Chilian High over Juan Fernandez (400 miles west of the continent). The latter is controlled by the conditions obtaining on the Antarctic ice plateau, which (as I have stated elsewhere) is as important a prime factor in world meteorology as the equatorial high-temperature belt. Thus when the cold Antarctic High surges north it gives the same movement to the eddies over South America, and Antarctic Lows are carried northward and give copious rains to Chili.

There is now a station (similar to our recent station at Macquarie Island) on Juan Fernandez. An equally valuable forecasting station is available for Australia at St. Paul Island (long. 80° E. and about 1,700 miles west of Perth), and it is to be hoped that a wireless station may be established there in the near future. Thus Mossman links up the Nile flood and the blizzard of the South Pole, and he believes that the relation is close enough for us to use the flood data inscribed on the Pyramids to learn something about the climate of Antarctica at that remote period!

In the next paper most striking curves are shown proving that the physical processes that bring about a high pressure in the Icelandic region are associated with a lowering of the pressure over South Georgia in the south temperate Atlantic areas. These opposite effects are exactly shown during May in every year from 1902 to 1912. Mossman believes the controlling factor is to be found in Antarctica. Can it be due to some difference in the time of freezing over of the pack ice around Antarctica? This usually occurs in May. If the sea remained unusually open it would tend to reinforce the Antarctic Low, while if it stayed frozen (i.e. did not break out) the permanent High of Antarctica would be able to expand to the northward.

Probably the most striking correlation given by Mossman is that between the summer temperatures of Cordoba (Argentine) and Alice Springs (N.T.). These places are both situated far inland, and have typical continental climates (see Fig. 202).

Thus the very cold weather at Alice Springs in 1904 was equally remarkable at Cordoba ; while the summer heat of 1900, 1902, 1903, and 1906 was pronounced in both localities. It is important to note that the eighteen years period before 1896 show no definite agreement. Perth (W.A.) and Valparaiso (Chili), both seaport stations, show a similar agreement during the period 1897–1910.

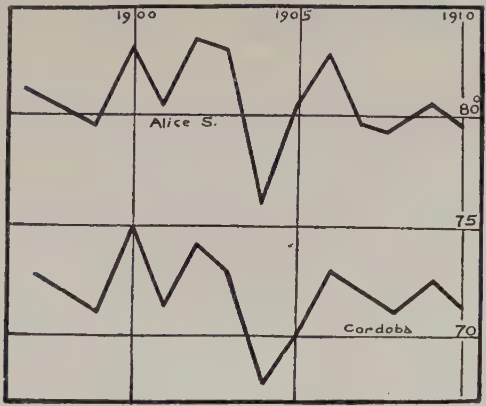

FIG. 202. Summer temperatures at Cordoba and Alice Springs.

Of even more interest perhaps is the relation evident between the rainfall of Trinidad and that of Azo, a port in the Argentine. Here heavy rainfall in Trinidad was followed—*six months later*—by a drought on the Argentine coast. This relation is almost exact for the period 1876 to 1894, and has a mathematical correlation coefficient as high as 0·79. In further studies of this type we may find the key to seasonal forecasting. It is to be noted that the correlation does not hold in *inland* stations in Argentine, hence the control would appear to be an oceanic one, which does not operate far inland.

But we must not become too optimistic. It is sad to find that these instructive correlations have a tendency to endure for twenty years and then lose ground and disappear for a time. This has been observed in several pairs of places which agreed for twenty years, and then lost touch with each other.

Mossman concludes: 'The action centres of the globe are probably subject to a cyclical oscillation of a more or less fixed period. The uncertainty underlying the persistence of correlation and non-correlation is due to most of the pairs of stations utilized being located not in "action centres" but in transitional zones, some doubtless coming at intervals under the influence of more than one pair of "action centres".'

THE CAUSE OF THE SECULAR CYCLES. None of the causes so far suggested seems to explain at all adequately this world-wide change in climate. Croll's theory depending on the varying distance of the earth from the sun is not now considered satisfactory.

Variations in the carbon-dioxide of the air have been put forth as factors in the problem. Changes in the shape and height of the continents have contributed largely, no doubt.

The change in the amount of solar heat received by the earth is probably the major factor. This may, however, be produced in part by terrestrial action, as the next section will show.

WORLD TEMPERATURES AND VOLCANIC DUST. In 1784 Benjamin Franklin blamed the dust blown out of Mount Hecla (Iceland) for the ensuing cold winter, intimating that it prevented the sun's rays from readily reaching the earth, and this is essentially the view advanced by Humphreys, though he justifies his theory somewhat more convincingly.

In the first place he determines the size of these volcanic particles by the coloured rings (coronae) which appear round the sun after an eruption. He finds that they are approximately 0·0000185 centimetres in diameter; and that it will take a year for these dust particles to fall from their upper limit (say 35 kilometres) to the isothermal layer (30,000 feet). Probably much longer is required for the majority of the particles, which are largely fragments of minute bubbles and therefore disk-like.

Now the effect of these particles on the heat waves thrown out from the sun, or radiated from the warm earth, depends essentially on the size (wave-length) of the waves. Approximately the earth rays are twenty times as large as those emanating from the sun. It is a physical law that the smaller waves from the sun (of somewhat the same size as the dust particles) are reflected from the dust, so that their value to the earth is greatly reduced by a stratum of dust in the upper air. On the other hand, the heat from the earth is not held back by the dust, but is scattered and largely lost from the particles.

Hence the dust acts in just the opposite way to the glass in a greenhouse, which allows the sunlight to enter but retains the stove heat.

Now let us examine how theory and practice agree. The amount of heat derived from the sun (insolation) can be measured in several ways. It is found to vary considerably, for instance in 1912 some measurements in Algeria showed that it was 10 per cent. less than normal. Let us now plot the curve showing this variation in the heat received from the sun. This constitutes the pyrheliometric curve. Humphreys calculates that in 1912 there was a theoretical diminution approximating to 10° F. in the earth's temperature. Actually this is of course greatly modified, but he is able to show that there was a lowering of 1° F. in the world's temperature in 1912.

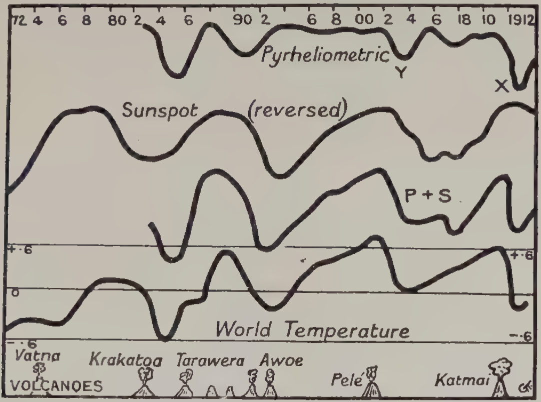

FIG. 203. The variation in world temperatures shown in relation to solar radiation, sunspots, and volcanic action, 1872–1912. Notice the volcanic factors at X and Y. (From Humphreys.)

The graphs shown in Fig. 203 are almost self-explanatory. They give the data since 1872, though a long series of graphs in the original paper show variations since 1750. The world temperature curve is seen to show well-marked cold periods—1884, 1894, 1903, and 1912. This agrees approximately with the sunspot curve *maxima*, and very closely indeed with a combination of the sunspot curve and the pyrheliometric curve (shown in Fig. 203 by the curve P + S). The latter depends on conditions of the earth's atmosphere, and its variations are probably largely determined by the huge amounts of dust thrown out at notable eruptions. These are shown at the bottom of the figure, and the coincidences after the gigantic outbursts of Vatna (Iceland), Krakatoa, Tarawera, Pelé, and Katmai (Alaska) are most striking.

Weather Cycles as shown by Growth-Rings. In a previous section it has been described how Mossman gave a clue to Antarctic weather in the time of the Pharaohs, and now I propose to describe the researches of Huntington on the climate of America since the time of Homer (see Fig. 204).

If we go into the Dandenong forests we can still see many examples of that mammoth tree which has the suitable name of *Eucalyptus amygdalina* (variety *regnans*). Three hundred feet is no very unusual height for our big trees, and we may safely reckon that such giants are many hundreds of years old. In California one of the big trees (*Sequoia Washingtoniana*) has been proved to be 3,210 years old. Professor Huntington writes of it as follows :

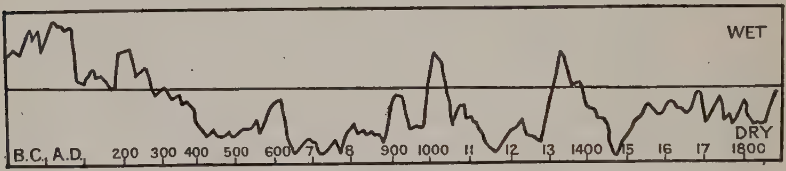

Fig. 204. Changes in climate in California for 2,000 years. (After Huntington).

> In the days of the Trojan War and of the exodus of the Hebrews from Egypt, this oldest tree was a sturdy sapling, with stiff, prickly foliage like that of a cedar, but far more compressed. It was doubtless a graceful, sharply conical tree, 20 to 30 feet high, with dense horizontal branches, the lower ones of which swept the ground. Like the young trees of to-day, the ancient sequoia and the clump of trees of similar age which grew close to it must have been a charming adornment of the landscape. By the time of Marathon the trees had lost the hard, sharp lines of youth, and were thoroughly mature. The lower branches had disappeared up to a height of 100 feet or more ; the giant trunks were disclosed as bare reddish columns, covered with soft bark 6 to 12 inches in thickness ; the upper branches had acquired a slightly drooping aspect, and the shiny foliage, far removed from the ground, had assumed a graceful rounded appearance. Then for centuries, through the day of Rome, the Dark Ages, and all the period of the growth of European civilization, the ancient giants preserved the same appearance, strong and solid, but with a strangely attractive approachable quality.

Now, how does Huntington discover from these trees the climatic variation during their growth ? Every one knows that in regions having an alternation of cold and warm seasons the trees grow more rapidly in the spring and summer, and merely 'mark time' during winter. This is shown in the arrangement of the new woody tissue. A 'ring' of wood is added each year, and this ring consists of larger and lighter-coloured wood cells in the growing period and of small darker cells during the resting season. Hence the alternation of light and dark rings in most trees grown in temperate regions. In very favourable years the growth may be twice as great as in years of diminished rainfall or cold temperature.

Professors Huntington and Douglass have made over 10,000 measurements of trees, including no fewer than 79 specimens over 2,000 years old. They have studied the growth rings of several genera of trees and have been able to eliminate factors which mask the variation due to climatic changes. Thus young trees always grow more vigorously than older trees, and their rings are proportionately wider and need a correction for the purposes of research.

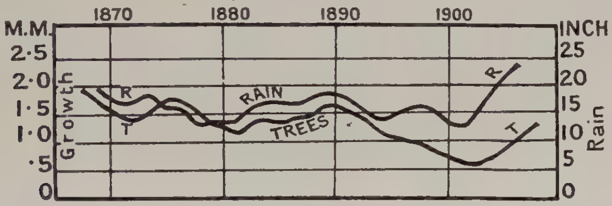

Fig. 205. Growth of yellow pine compared with rainfall at Prescott, Arizona. In both cases curves are smoothed by five-year means. (After Douglass.)

They conclude that the variations in the annual rings of individual pine trees in the dry regions of northern Arizona exhibit such uniformity that the rings of one tree can be identified in others over large areas, and the date of their formation established with practical certainty (see Fig. 205). The ring thicknesses are proportional to the rainfall with an accuracy of 70 to 82 per cent. in recent years, and this accuracy presumably extends over centuries.

The ring record at Flagstaff, Arizona, has been traced back 500 years, and various cycles found in it. An approximate 33-year cycle shows in the last 200 years. A 21-year cycle shows in 400 years, and an 11-year cycle displays a similar duration. The 11-year cycle is, of course, the sunspot cycle, and this is remarkably shown in the growth rings of certain pines measured in northern Germany.

Professor Huntington has collected data from trees, and from the ruined villages of western United States of America and Mexico, from western Asia, and from archaeological records generally. As a result he has plotted a curve showing climatic changes since 1500 B.C. As he says,

> 'Such knowledge of past cycles is essential if we would understand the varied and important effects which climatic pulsations, working through famine, migration, and other causes, have produced upon man in the past and are likely to produce on him in the future. Long records are essential if we would understand what has really happened in the past, and thus put ourselves in a position to determine the causes of the present changes and to arrive at the ability to predict those of the future.'

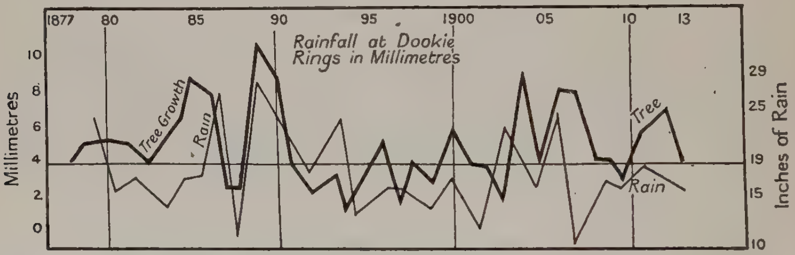

FIG. 206. Graph of the rainfall and the growth of a tree at Dookie, Victoria.

Now, with regard to similar investigations in Australia. For some time past the Commonwealth Meteorologist has been collecting cross-sections of trees with a view to testing these hypotheses. It is too early to anticipate much accuracy from the method yet, for we have not sufficient data for the preliminary investigations, but some relation obtains between the growth-rings of one polished specimen and the rainfall.

A specimen of yellow box was forwarded by Mr. C. S. Heape, from Mount Major, near Dookie (Vic.). The slab is 3 feet across, being rather wider along an east–west than a north–south axis. This difference may be correlated, as Mr. Hunt suggests, with resistance to the prevailing westerly winds. The growth-rings are fairly distinct, and vary in width from 1 to 10 millimetres. The tree shows about 130 rings, and is therefore probably over 120 years old. It was cut down on 19 February, 1913.

One specimen cannot, of course, give an accurate result. Where faults in the series occur, it is necessary to interpolate from adjoining sections, but the graph certainly shows a close relation (see Fig. 206). The horizontal line represents the average rainfall at Dookie (19 inches), and also the average ring width (about 4 millimetres). The curves show the relation since 1877. They agree very well since 1887. Before that, it appears as if too many rings had been inserted. Possibly abnormal rains have caused two periods of rapid growth in a year. The central wood of the specimen is not very favourable for the research, being apparently shrunken and somewhat split.

This method, elaborated by Douglass and Huntington, is by far the most accurate which we possess for investigating past cycles, and it furnishes perhaps the most hopeful guide along the thorny path of the weather-cycle forecaster.

CLIMATIC CYCLES AND EVOLUTION. In a recent memoir[1] the writer advances the hypothesis that the geological record shows evidence of two climatic cycles—a major and a minor. The major cycles are about 150 million years apart, and three have occurred since Early Cambrian times. They culminated at the Early Cambrian, Devonian, Permian, and Tertiary Epochs. In intervening ages the climate of the world was warm and relatively uniform from the Arctic to the Antarctic circles. At the culminations we get rapid changes in climate, gradually producing Ice Ages in temperate latitudes and giving the zonal type of climates with which we are familiar. It is at these culminations that evolution has progressed most rapidly.

The minor cycles are about 200,000 years apart and are well shown by the alternation of Ice Age and Interglacial in the Permian and Pleistocene Epochs. The 'climatic thrusts' of the four Pleistocene Ice Ages have led to the evolution and migration from Central Asia of the four races of man—the 'black', brown, olive-white, and yellow. The latter seems to be the latest type developed.

On this hypothesis, we are now living in an Interglacial period. The cool arid lands of latitude 35° will gradually become warmer and still drier, while the warm arid lands of latitude 20° will become wetter. Gradually Ice-Age conditions will return, and southern Australia will become much wetter, cooler, and generally better suited for close settlement. This 'long-range forecast' is an epitome of the climate for the next 100,000 years!

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[1] *American Geographical Review*, December 1919.

CHAPTER XXV

AVIATION AND METEOROLOGY

Commercial Aspects. In the days of the sailing ships it was imperative that every master should understand the course of the permanent winds, the tracks of the chief ocean currents, and the laws governing the origin and structure of storms. With the advent of steamships this knowledge is perhaps not quite so vital to the seaman, but its advantage to the navigator of the air should hardly require stressing.

The aviator's track is not limited to one plane as is the seaman's —so that his problems are much more complex. He must not only know the meteorology of the lowest layers of the atmosphere, but also as much as possible of the controls governing the weather up to 20,000 or 30,000 feet above the surface.

There is a purely commercial aspect of this study which has lately been set forth by Lord Montague.[1]

> 'It is clear that meteorology and the study of wind currents are going to be of supreme importance. The knowledge of the world's atmospheric conditions and accurate forecasts, apart from their inherent scientific interest, may effect the saving or spending of millions of money annually when postal and commercial aviation is established.'

A short Course for Aviators. What branches of meteorology will be of most service to the aviator ?

When I started my lectures at the Commonwealth Aviation School in August 1914 the literature on the subject was scanty in the extreme. Even after four years of war there is no complete study which can be placed in the hands of the thousands of aviators from Europe, America, and Australia.

The following list gives those papers which have been found of most value.

(1) *Aeronautical Journal*, London. (Articles by Napier Shaw, Major Taylor, Brewer, and others.)

(2) Humphreys, *Holes in the Air*. (Smithsonian Reports for 1912.)

(3) Ward, *Meteorology and War Flying*. (U.S.A. *Weather Review*, 1917.)

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[1] *Geographical Review*, November 1917.

(4) J. S. Dines, *Wind Structure.* (Various official papers, London Meterological Office.)

(5) *Forecasting in U.S.A.* Memoir of *U.S.A. Weather Service*, 1916.

The two small books by Napier Shaw, *The Weather Map* and the *Glossary*, will be found very useful by aviators. They are published by the London Meteorological Office.

In a short course of a dozen lectures, it is impossible to teach more than the main principles of some branches of the subject. In the first six lectures I would suggest that temperature and pressure changes and their effect on the weather—especially as regards wind, rain, and fog—are the chief features dwelt upon. Three lectures deal with weather charts and the elements of forecasting. Upper air research, in so far as it enables us to understand the winds of the troposphere, is treated in another lecture. Special aviation problems are considered in two lectures. Lastly I have usually given one lecture contrasting the meteorological controls in Europe with those in Australia.

In our service the instruction is based on Australian conditions where *inter alia* all the dynamic problems differ radically from those usually described, since the Ferrel effect causes a deviation to the left. Moreover, we are concerned primarily with the high-pressure belt, whereas in Europe and the United States the low-pressure belt is perhaps the dominating feature.

The aviator would do well to study especially the following chapters in this text-book: The Weather Chart (II), Work at the Station (III), Temperature (VI), Pressure (VII); Winds (VIII), Pressure Gradient (IX), Water Vapour (XII), Rainfall (XIV), Upper Air Research (XXII), Forecasting (XXIII), and the present chapter.

Special Aviation Problems. These may be summarized as follows:

A. Surface conditions deduced from ordinary weather charts.
B. Flight conditions from the surface to 10,000 feet.
  (1) Variations in atmospheric density.
  (2) Variations in wind direction.
    Steady horizontal winds.
    Turbulent winds.
      Aerial fountains.
      Aerial cataracts.

(3) Variation in wind velocity.
    Wind gusts. Wind bumps.
(4) Winds at different layers.
(5) Changes in temperature with height.
(6) Changes in humidity.
(7) Cloud effects. Fog effects.
(8) Topographic effects.
    Deflection eddies.
    Convection (heat) bumps.

Surface Conditions. Unless there is a forecaster especially attached to the aviation school, it is obvious that the forecasts from the public bureau will need adapting to local conditions. If, for instance, the school lies forty miles *to the west* of the bureau, it will in general be affected by oncoming storms two or three hours *before* the bureau. Hence it is better to receive forecasts from a station *to the west*, if any choice be possible.

Every locality has its own topographic effect. Thus at Laverton (Vic.) the land and sea breezes differ markedly from the winds at Melbourne some twenty miles away. An aerodrome will be chosen in open country if possible—but some surface irregularities are sure to be present, and these break up the lower layer of air, as we shall see in discussing obstructions.

The reports of the aviators' experiences should be collected and discussed in terms of the daily weather chart. In this way only can the idiosyncrasies of the aerodrome be recognized and allowed for in future courses of instruction.

Special forecast messages could readily be arranged for, in which the bureau at 9 p.m. could give the probabilities for flight at 4 a.m. following. An intelligent study of the charts should enable any flight-instructor to make these short-period forecasts for the aerodrome with a reasonable chance of success.

Density and Pressure of the Air. Humphreys has very effectually disposed of the old belief that 'bumps' were due to local *vacua* in the air by pointing out that if anything approaching a vacuum did occur the air would rush in at a speed of 750 miles an hour!

The lowest (surface) pressure occurs within a tornado or hurricane and is somewhere about 27 inches in our latitudes. Needless to say, aviators do not often experience these conditions: yet even here the actual density is no lower than can be reached by an ascent of 3,000 feet ! In both cases a reduction of density by only one-tenth results. ' Bumps ', as we shall see later, are due to changes in direction or velocity of wind layers, and not to variations in the actual density of the air.

The atmospheric pressure is about 15 lb. per square inch at sea level, and decreases about half a pound per square inch for each 1,000 feet of ascent. Thus it is about 10 lb. at 10,000 feet.

We may note that when the pressure is higher (or the temperature lower) the performance of the engine is better.

WIND DIRECTION. The most casual observation of cloud movement will show us that the various layers of air are usually moving in different directions. For instance, over Melbourne the cirrus moves fairly regularly from the west, no matter what the surface air is doing.

In these layers, moreover, the air currents may not keep to one plane. A sort of wave motion is indeed apparent in most of the upper clouds, where it is rendered obvious by the ripples carrying condensed moisture or particles of ice.

In the lower layers of the air these indicators are not present, but we have direct evidence of their existence.

On 9 December, 1912, an intense Low passed to the south of Melbourne accompanied by violent west winds. Considerable damage was done (about 10 p.m.) to buildings at four different localities along the track from Flemington to North Richmond (see Fig. 207). The intermediate regions were not harmed ; and as these gaps are of equal length the inference that recurrent waves of rapidly moving air were concerned is quite legitimate.

Professor Payne investigated the wind forces which blew down heavy brick chimneys at the University, and found that a wind of 82 miles an hour was necessary to overthrow the chimneys.[1]

At the bureau a velocity of only 45 miles was reached, though it is only half a mile away from the University. This figure of 82 miles is the record for Melbourne, though the Brighton tornado (6 miles to the south) certainly exceeded it.

Probably many of the layers above 1,500 feet consist of streams of air moving in fairly horizontal paths. These layers may be separated by belts of almost stagnant air, or the transition may be gradual or quite abrupt from one moving layer to the other.

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[1] Described by Professor Payne before the Vic. Inst. Engineers, December 1912.

A special predicament here confronts the aviator. If he be flying with a speed of 50 miles an hour to the west against an east wind, and sinks down into a lower layer of exactly his own speed and direction, then his machine will receive no support whatever from the air. As Humphreys says, 'All dynamic power is lost, and all guidance, and a disastrous fall is probable.' It is of course easy to change either the engine speed or the direction or both, and so alter the conditions. But it would appear wise for beginners to be cautious if the air is sharply layered as postulated. With modern high velocity machines the risk is reduced to a minimum.

Turbulent Winds. Two special types of air movement have been compared by Humphreys to 'fountains' and 'cataracts'.

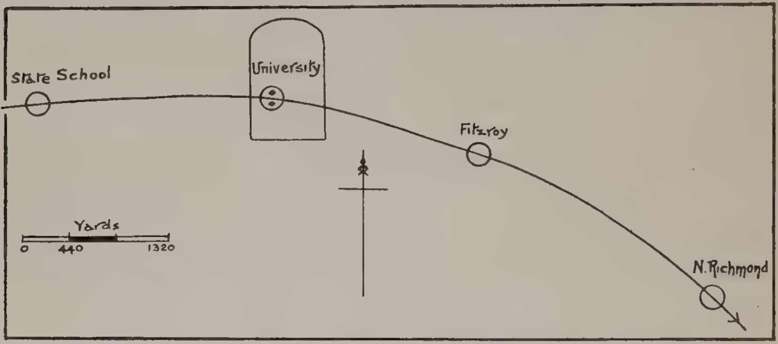

Fig. 207. Intermittent damage by westerly squall at Melbourne on 9 December, 1912.

Beneath a cumulus cloud is a column of ascending air which may be rising at the rate of as much as 30 feet per second. This aerial 'fountain' undoubtedly gives rise to 'bumps' as the plane passes from the undisturbed air into the convection column.

One of my class (in the Eleventh Aviation School) kindly supplied the following description of such a 'fountain':

At 8.3 a.m. on 2 August, 1917, there was a south-east wind at the surface about 10 miles an hour. On flying near the lagoon by Laverton Station at about 3,000 feet a column of rising air seemed to be encountered, which lay somewhat to the lee (or west) of the lagoon. The machine dropped 30 feet on entering this column. Above this bumpy area lay a cumulus cloud, and it is not quite clear whether the rising column was connected with the lagoon below or the cumulus above.

On another occasion the aviator lost 40 feet of altitude on entering the column and felt an upward bump on leaving it. He was 3,000 feet above ground.

The edge of the column is usually more bumpy than the interior, where conditions are more uniform. If the flight passes along the edge of the 'fountain' a general tossing of the machine is to be expected.

An *aerial cataract* may occur at the front of a thunderstorm where the air is rolling over and over to form the characteristic 'squall-wind'. This would be a dangerous area for an aviator, and a descent would probably be advisable if the storm covers a large extent.

GUSTINESS. The anemometergraph shows that the wind stream is made up of numerous 'filaments' of very different velocities, and the velocity of the wind is merely the average velocity of all these separate 'strands' (see Fig. 208). This gustiness has a considerable effect on flying; for the lifting power of the wind depends directly on its velocity.

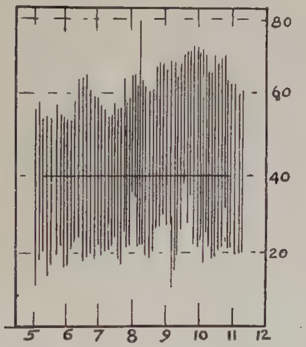

FIG. 208. Gustiness shown at Holyhead. The ordinary range is between 20 and 60 miles per hour. There are occasional excursions to 80 miles an hour. (After Napier Shaw.)[1]

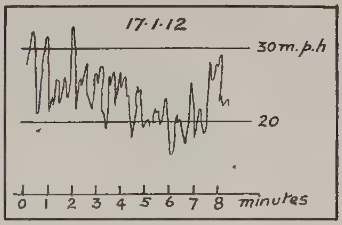

FIG. 209. Ordinary 'gustiness' disclosed by a 'quickrun'; showing two gusts per minute. (After Napier Shaw.)

The following graph (Fig. 209)—from Napier Shaw—shows that there are from two to thirty of these gusts in a minute.

The soaring of birds is probably due to their taking advantage of these momentary changes in wind velocity—for by varying their own direction and the inclination of their wing-planes, they are able to float, without flapping, for an almost indefinite time.

Very little has, however, been published on gustiness as applied to aviation, except the paper by Shaw in the *Aeronautical Journal* for 1914—from which the above figures are taken.

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[1] Figures at the Base of Fig. 208 are hours.

Ward defines the fluctuation of the wind as the difference between the average maximum velocity reached in the gusts, and the average minimum velocity in the lulls.

Gustiness is defined as the ratio of the fluctuation to the mean velocity.

Many of the 'bumps' experienced by aviators are due to gustiness. The latter originates largely in the obstructions which the wind meets in the lower layers of the air.

Above 4,000 feet both wind bumps and heat bumps (q.v.) are comparatively rare, for here neither the effects of convection nor of surface friction are felt to anything like the same extent.

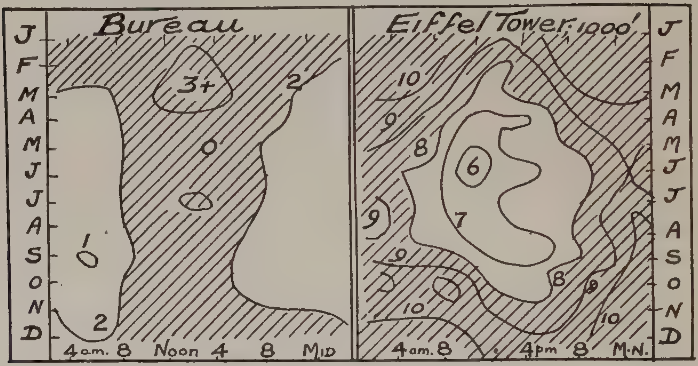

Fig. 210. Graph at Paris showing that the wind velocity is highest at 2 p.m. on the surface, but at midnight 1,000 feet up. (Figures are metres per second.) Higher velocities are ruled. (From *Aero. Jnl.*, 1914.)

In the lowest layers of the atmosphere it is quite usual for one wing of the plane to be in a stream of air at, say, 10 miles an hour, while the other may meet air moving at 8 or 12 miles an hour. The result is that jerks are produced, and sudden drops are but too common.

Espy's Theory of Mingled Layers. It is an interesting fact that though surface winds reach a maximum velocity about 2 or 3 p.m., and a minimum velocity in the early morning, yet the wind velocities at the chief flying levels (from 1 to 3,000 feet) exhibit just the opposite conditions.

This is well shown in the graphs taken at the Eiffel Tower throughout the twenty-four hours (Fig. 210).

The theory propounded by Espy in 1840 explains this variation.

At the surface, convection is at a maximum in the hottest time of the day. A series of columns of air rise from the ground and pass through the lower wind layers to the upper layers. Here they protrude into the latter, acting as links or pegs uniting the lower air to the more freely moving air of the upper layers.

The consequence is that the lower air to some extent participates in the greater velocity of the upper air, but acts as a drag on it, causing the average velocity of the latter to decrease.

In the night there is no convection. The upper layers flow on, more or less without mingling with the lower layer. The latter is entangled among the hollows and obstructions of the earth surface, and lies as a stagnant chilled stratum with much less mobility than it exhibits in the day time.

As pointed out in the chapter on winds, since it is advisable for beginners to fly in the quieter hours of the day, the hours from 4 to 8 in the morning and from 5 till 8 in the evening are chosen.

WINDS AT DIFFERENT LAYERS. At the Laverton Aerodrome there are often three well-defined layers. The lower 500 feet is affected by the local land or sea breeze; for the hangars are on the north-west shores of Port Phillip, which is a circular sheet of water 25 miles wide.

Above this surface wind, there blow the winds of the pressure-system shown on the chart. Usually south-westers in front of a High, or northerlies in front of a Low. These extend up to 3,000, 4,000, or 5,000 feet or more.

Above the isobaric winds (as we may term these winds agreeing with the isobars on the weather chart) the aviator almost always reaches the westward drift, generally about 4,000 feet.

Often of course there is no land or sea breeze, and then the isobaric winds blow at the surface. Quite usually the surface wind is a deflected isobaric wind, the actual wind being the resultant of the isobaric and the land (or sea) breeze.

As noted previously, the winds around the Highs and Lows are inclined to the isobars at the surface; but at about 1,500 feet up, they blow *parallel* to the isobars.

Hence the south-west wind of the surface High tends to become more of a south wind above; and the north-east wind twists more to the north as the gradient wind (q.v.) is reached.

In the far north of Australia the conditions recorded by Van

Bemmelen of Batavia probably apply fairly closely. He gives the following table: (N.B. a kilometre = 3,280 feet.)

Height in Kilos.	*Direction.*	*Velocity.*
30–23	Easterly wind	40 metres per sec. (90 m. p. h.)
23–18	Westerly wind	10–15 metres per sec.
18–17	Upper easterly	Low velocity
17–3	Anti-trade	Up to 23 metres per sec.
3–0	Trade wind (SE.)	5 metres per sec.

Blair's diagram, in the chapter on Upper Air Research, should also be consulted. (Fig. 187).

CHANGES IN TEMPERATURE AND HUMIDITY. These have not much influence on aviation except as regards the comfort of the aviator. It is difficult to gauge temperature changes, for the warmth of the engine and the effects of flying with or against the wind are two factors which make it almost impossible for the aviator to obtain a reliable record.

My own attempt in March 1917 was quite unsuccessful, partly for these reasons and partly because the jolting jerked the ink off the pens in the Fuess Meteorograph which was lashed in front of me.[1]

High humidity may affect the petrol mixture in the carburettor, but to no greater degree than in a car on the surface.

CLOUD EFFECTS. Some of these have been noted already, when due to convection or thunderstorms. (See p. 130.)

The most obvious perhaps is the almost total absence of all guide to direction.

Captain Hucks (in the *Scientific American,* 6 October, 1917) describes an ascent in the west of England on a very cloudy day.

> At 1,200 feet he reached dense rain clouds and was still in them at 5,000 feet. Then the compass appeared to swing erratically, which was due really to the plane being caught in turbulent air. The air speed rushed up beyond normal flying speed, and all efforts to pull up were of little use. He was literally tumbling about in the clouds, and emerged therefrom nearly upside down!
>
> On another occasion he relates how he lost his bearings in a dense cloud, so that everything loose in his machine fell out!

On the other hand a uniform layer of stratus, or non-convectional cloud, is an indication of steady air and often assures very good flying beneath it.

---

[1] See *Australian Monthly Weather Report* for July 1913, p. 371.

Topographic Effects. (*a*) Convection.

Since the specific heat of various substances forming the surface covering varies considerably, it is not surprising to find that the sun's heat has correspondingly different powers.

Such surfaces may tentatively be arranged in the following order :

Decreasing scale of convection effects.

1. Houses and factories.
2. Streets.
3. Bare rocky hills.
4. Ploughed fields.
5. Grass.
6. Forests.
7. Large lakes.
8. The sea.

[As in most of these problems, very little research has been carried out on convection. Most of this chapter is merely suggestive, and will need considerable corroboration before the explanations can be deemed conclusive.]

The great difficulty in gathering evidence as regards heat-bumps (which result from convection) is that conditions vary considerably before and after sunrise. Thus a small lake will often be warmer than the land during the night, and so may generate a column of ascending air in the night. But when the sun has been up for an hour or two, the surrounding land will be warmer than the lake, and the latter will perhaps be a centre of somewhat stagnant air ! Since most flying occurs just after sunrise—at the schools at any rate—it is not surprising to find students perplexed by the different kinds of bumps encountered over the same area.

I give here a few accounts by students of heat-bumps of this nature, with the caution that the interpretations may need modification later.

(*a*) In the early morning a decided drop is experienced when crossing over a sheet of water, and a bump-up when crossing a ploughed field. Later in the day these conditions are exactly reversed. (See explanation above.)

(*b*) On reaching the small lake to the north-east of the School a drop of 10 feet was felt, a series of smaller bumps on crossing the water, and a sudden rise on the opposite margin. (This seems to indicate light moist air—but is perhaps exaggerated.)

(*c*) On crossing from land to sea a bump is often felt at most altitudes up to 1,000 feet. (N.B. The writer has on several occasions tried crossing from the aerodrome to Port Phillip, but has not felt this bump.)

(*d*) The bump, &c., often occurs to leeward of the surface agent. Thus one student dropped 25 feet when over the *middle* of a swamp (and 100 feet above it). When about 150 feet to lee of the swamp he experienced an upward bump of about equal magnitude. (The light southerly wind had drifted the moist air about 150 feet to the north from the swamp.)

(*e*) A macadamized road (when the plane is about 150 feet up) will give a bump 20 yards to the leeward, if there is a moderate surface wind.

My late colleague at the Commonwealth Flying School, Flight-Lieutenant Sleeman (an engineer and instructor in flying), has very kindly given me the following notes on convection effects, especially as regards this problem of the drift of the column to leeward.

'The effects of convection in Victoria may be experienced at altitudes up to four or five thousand feet, depending on the season of the year, the surface of the ground, the velocity of the surface winds, cloud effects, and time of day.

'The surface winds tend to flatten out the bumps in much the same way as heavy rain will flatten out a choppy sea. They also make the diminished effect of the bump felt to leeward of the spot from which the bump actually emanates. The amount of flattening out is increased as the velocity of the wind increases.

'On the 19 December, 1916, at 11 a.m., whilst flying over Werribee at 2,000 feet, with a south-west surface wind with a velocity of 20 miles per hour, the effect of the bump from the sea was noted four miles inland, and the effect from the Werribee River two miles north-east of the river.

'On the 24 September, 1917, at 11 a.m., with a southerly surface wind of 25 miles per hour, whilst flying over Melbourne at 4,000 feet, the effect of heat-bumps was decidedly violent. The deflection in this case was approximately four miles north.

'On the 25 September, 1917, at 3 p.m., with a south-easterly surface wind with a velocity of 15 miles per hour, whilst flying over Melbourne at 5,000 feet, the effect of the bump was more marked than at 4,000 feet on the previous day, the deflection in this case amounting to only two miles.

'With a (partially) overcast sky the effect of heat-bumps is much more marked at a given altitude with a given temperature and surface wind velocity than with a clear sky. The bumps are more violent and the effect extends to a greater altitude.

'On the 30 April, 1917, at 5 p.m., with an overcast sky, the effect was so violent that at 1,000 feet control of the machine was exceedingly difficult, whilst at 4,000 feet the effect of the heat-bump had not diminished.

'On the 7 August, 1918, at 9 a.m., the same effect was noted.

'The effects of heat-bumps in summer months with a moderately clear sky is not usually noticed until about 8 a.m., after the sun is a considerable distance over the horizon. On the other hand the effect of the heat-bump was felt considerably after sundown on the 4 February, 1917, whilst flying over the aerodrome at 4,000 feet at 8.30 p.m.'

(*b*) Obstacles. That eddies and turbulence are caused by the wind passing over buildings, trees, hills, or mountains was only to be expected.

Humphreys shows that the lee side of a steep ridge (placed across the wind) is especially to be avoided. The same rule applies to buildings, for the wind tends to descend in a swirl on the lee side. Humphreys counsels a landing parallel to the ridge *along the axis* of the swirl, for here the motion will be more uniform.

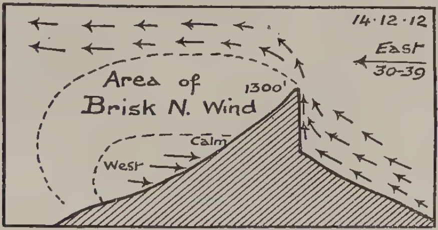

Fig. 211. The effect of a Rock Ridge 1,300 feet high (Gibraltar) on the wind structure. (After Harries.)

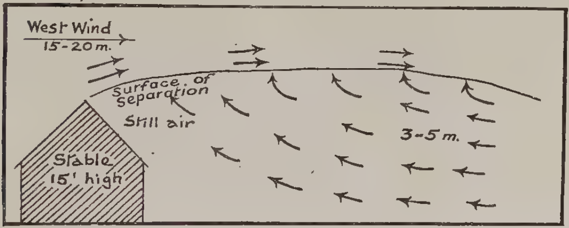

Fig. 212. 'Cliff eddy' behind stable at Pyrton Hill. (After Napier Shaw.)

Some investigations by Harries on the deflections at the Rock of Gibraltar are illustrated in Fig. 211.

Here when a strong east wind was blowing, there was a westerly breeze low down on the lee side. A small space of calm separated it from a great area of northerly wind, and above this again was the east wind. With a mild east wind this northerly belt was absent (*Aeronautical Journal*, July 1914).

As the wind strikes a building or a belt of trees it is forced upwards, but the crest is often somewhat to the lee of the obstruction. Some experiments by Dines on this effect are illustrated in Fig. 212.

Most of these bumps would hardly be felt in a rapidly-moving aeroplane, and it is a distinct handicap in flying that the learner must practise in the most turbulent (lowest) layer, and must fly slowly at first when the plane is much less stable than when it is moving rapidly.

A METEOROLOGICAL FLIGHT IN AUSTRALIA. The weather chart, plan and elevation, relating to a flight made by the writer in March 1917 have some points of interest and are given in Figs. 213–15.

For some days the south of Australia had been dominated by low-pressure systems.[1] On the 13th the day was warm and cloudy. The wind was northerly long enough for a fairly high temperature (85° F.) to arise, and as the relative humidity was rather high the heat was somewhat oppressive. The barometer at 3 p.m. was unusually low for Melbourne, recording 29·44 inches. Hence, although there was no storm centre developed, the conditions were very favourable for experiencing ‘ bumps ’ and allied phenomena (see Fig. 213).

On this occasion Flight-Lieutenant Galloway was the pilot, and he has kindly supplied me with some notes from the aviator's point of view, which I have embodied in the following account.

The wind at the surface was between north and west, and was rather variable, but with low velocities. We started at 3.30 p.m., and ‘ taxied ’ over the ground to get clear of the hangars, curving to the west. Here we faced the wind—the most favourable way to commence an ascent—and soared off the ground towards Werribee. (See Fig. 214.) I had asked Lieutenant Galloway to cross from grassland to dry plain, and from land to sea, so as to see if the Fuess meteorograph which I carried would record the ‘ bumps ’. [These arise when the plane enters or leaves the ascending currents, which develops over warm surfaces.] Lieutenant Galloway writes :

‘ The ground conditions were not at all ideal for flying. The wind was about 20 miles per hour and gusty, and the atmosphere inclined to be close, so that we were subject to “ wind bumps ” as well as “ heat bumps ”, the latter in a lesser degree.

‘ Up to 2,500 feet conditions were such that I would not have continued on a pleasure trip, but anticipating better above—and in view of the fact that we were on an observation flight—I put up with the discomfort of the existing conditions.

‘ At 3,000 feet the atmosphere was distinctly smoother, the heat bumps entirely disappearing, and only an occasional gust needing any correction by the pilot. At 4,400 feet the flying was quite smooth. Then we apparently ran into a belt of “ low density ” air for about ten minutes or more, since it was quite impossible to get the machine to climb until we were over the sea, when no difficulty in climbing was experienced at all.

‘ On the whole I found that the machine climbed better over the sea than over the land, although I do not think this difference is apparent after 5,000 or 6,000 feet.

---

[1] A flight under Anticyclonic conditions on 27 October, 1915, is described in *Aus. Weather Report*, No. 7, Vol. 4.

'The most bumps were felt over Werribee, the Werribee River, and the edge of the Sewage Farm.'

It was soon evident that the Fuess was not braced to resist the vibration of the plane. The three pens jerked violently, so that the ink flew off the barograph pen. The record was only half an inch long for the whole trip, and it is obvious that the time scale must be altered. Mr. Hunt suggests the use of a belt from an intermediate pulley, driven by a separate clock.

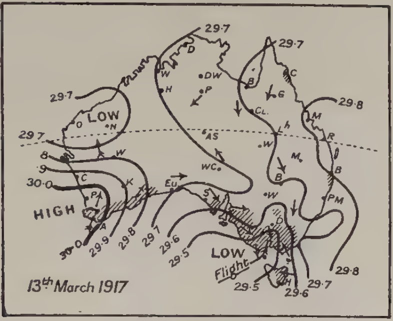

FIG. 213. Chart showing the Low dominating the weather, during a flight from Werribee to Melbourne.

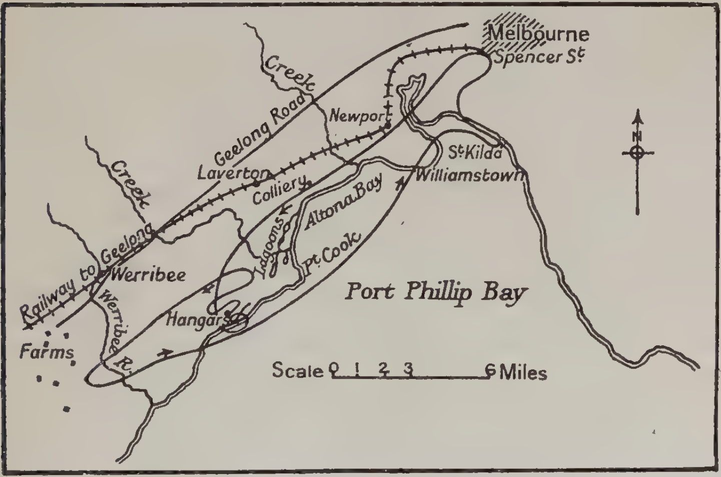

FIG. 214. Plan showing the surface features influencing a flight on 13 March, 1917.

At first we were flying over the mouth of the Werribee River and adjacent farms to the south of the hangars. Here the alternation of bare ground and green crops caused very conflicting vertical currents. No sooner was the speed of the propeller adjusted to the conditions in one patch of air, than we entered another, where the topographic effect was quite different, with the result that the lifting effect of the air varied greatly, and the plane experienced a 'bump' in consequence.

The peculiar conditions about 4 p.m. when the plane found unfavourable air at 4,000 feet were perhaps due in part to damp air arising in isolated columns from the small lakes and swamps near Point Cooke.

But the difficulty arising from what aviators call 'low-density' air was probably in part due to our attempting to fly to the east in a layer of air of about the same velocity and with the same direction. For reasons stated earlier, conditions are here unfavourable.

A slight change of direction and speed, coupled with the steadier air over the Bay, enabled us to leave this belt and progress rapidly on our way. We planed down to 3,500 feet and flew out over Port Phillip Bay. Here the air was stable and the plane ascended steadily again to 4,500. By this time we had crossed Williamstown and skirted along the Melbourne piers to St. Kilda (Fig. 214). We turned here and, still ascending, flew over Spencer Street and Newport, where the factory smoke below us showed that there was then practically no wind at the surface. We were now proceeding south-west over Altona Colliery and gradually rising to 6,500 feet.

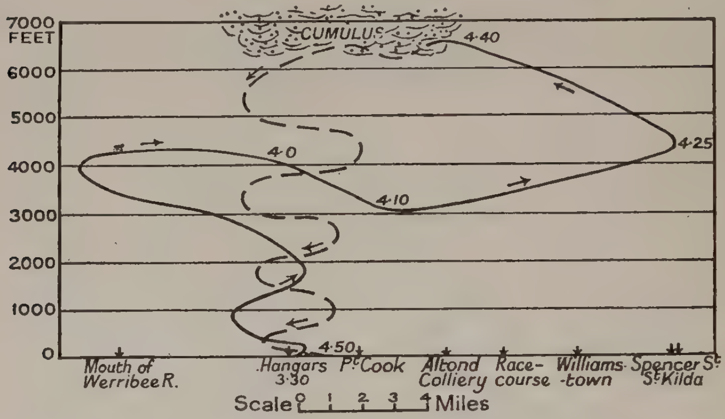

FIG. 215. Elevation of flight showing position of cumulus, &c.

After investigating a belt of cumulus (as described on an earlier page) we spiralled down 6,000 feet in 7 minutes towards the hangars. Our petrol supply had given out, and we were forced to land some distance to the north, reaching the surface at 4.50 p.m.

THE AIR ROUTE TO AUSTRALIA[1]

The advent of steam has decreased the economic importance of surface winds and currents, but the sailing ships in the Australian trade are still bound by weather laws and have only one route. They come from Africa to Australia and return to Europe via Cape Horn. The reverse route—though possible—involves permanent head winds and unfavourable currents which take it out of the realms of economic trade. Much more will the air routes depend on the variations of weather and climate.

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[1] Written 9 January, 1919. Published in *Am. Geogr. Rev.*, April 1919.

As we have seen in the first chapter, the study of surface winds and of the general circulation of the atmosphere dates back to very early times. It is, however, only in the last twenty years that the exploration of the upper air has been carried out at all generally, but now research is world-wide. For instance, in 1911 Simpson first sent up sounding balloons in Antarctica (where the writer was initiated), and in 1913 and 1914 the upper air of Australia was investigated in the same way at Melbourne.

Like so many scientific experiments, their immediate practical value was not obvious to the man in the street. Now, however, that aviation has come to its own, these explorations of the upper air have already proved of value. The American Government has devoted $100,000 to meteorological research connected with military aviation; and it is to be hoped that our own military and political authorities will show more interest in the future than they have hitherto done in the matter.

Let us now see which are the most promising routes to our isolated continent. In Fig. 216 (on Sylvanus's projection) the position of Australia with regard to the other continents is well brought out. Though the edges of the map are necessarily distorted, it shows us that Australia is situated in the centre of the largest expanse of water in the world, which we may term the Pacifico-Indian Ocean. This sheet of water is itself surrounded on all sides by land except to the south of Africa—for Antarctica entirely shuts off the waters to the south of Australia—and this ocean will for long prove an obstacle to flights from most of the continents.

If we draw a circle of 4,000 miles radius from Canberra (which is happily placed almost at the centre of population of Australia), we find that it passes right through Antarctica (near the South Pole), but includes none of the other large masses. Our nearest continent is therefore of little use as a flying dépôt. Africa and the Americas are ruled out by distance; they are separated from us by 7,000 miles of water, with but few islands in most directions. There remains, therefore, Asia—and it is by way of India and the Straits Settlements that we may expect our earlier aeroplane services to travel.

Nature has placed stepping-stones from India to Australia in the form of the drowned volcanic ranges, which are, of course, the islands of Sumatra, Java, and Timor ; and these lead directly to Darwin, the chief settlement on the north coast.

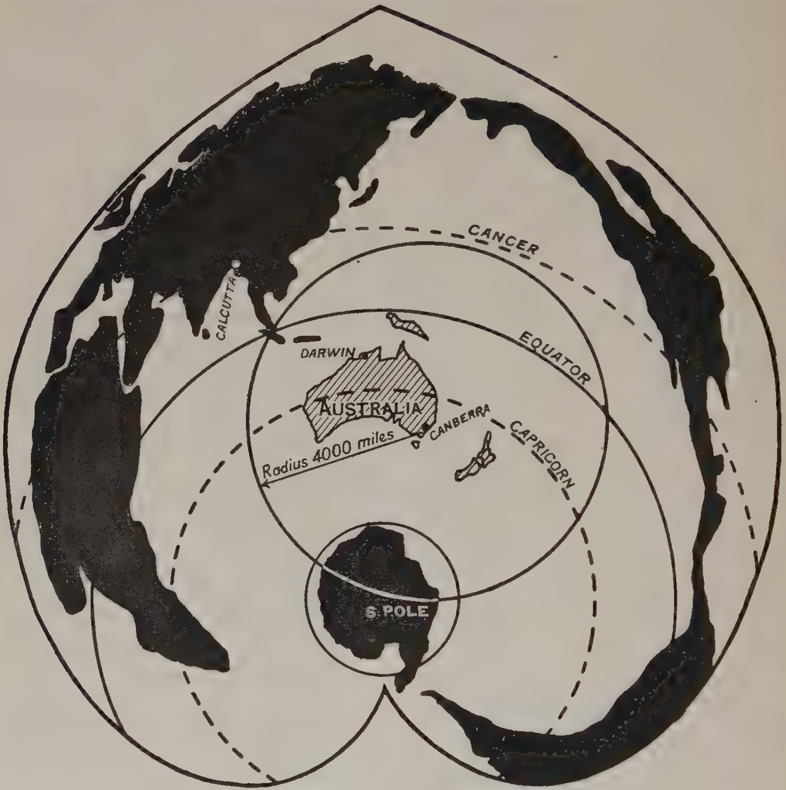

Fig. 216. The isolation of Australia by the great oceans.

The recent flights (in 1918) from England to India were accomplished with comparative ease in about four days, and will soon become almost weekly occurrences. I have drawn up a list of stations from Calcutta to Canberra with their distances. At all of these, except perhaps Koepang and Mataranka, there are, I believe, stores of petrol and facilities for repair (see Fig. 217).

As regards the time occupied, Lord Montague in his paper on the World's Air Routes assumes about 1,200 miles per day as the average passenger-plane speed. Mr. Holt-Thomas in a recent lecture before the Aeronautical Society showed a map of the world crossed by air routes, where Sydney is only five days from England. This is twice as rapid as the recent flight, and is probably much more rapid than the earlier services are likely to accomplish regularly. I have assumed 1,500 miles in twenty-four hours, which makes it about four days from Calcutta to Canberra, allowing for favouring winds.[1]

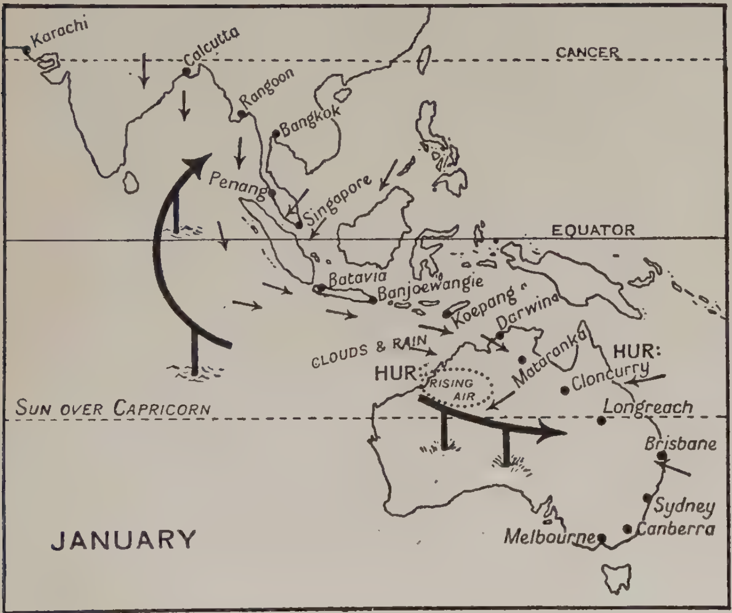

FIG. 217. The dominant winds in January. Those of the upper flying layer are on stilts.

First Day		*Second Day*	
	—Calcutta.		—Penang (Malay States).
650	Rangoon (Burmah).	350	Singapore (Malay States).
350	Bangkok (Siam).	560	Batavia (North-west Java).
580	Penang (Malay States).	520	Banjoewangie (South-east Java).
1,580 miles.		1,430 miles.	

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[1] This footnote is written the day Ross Smith and his gallant mates reached Darwin. They left London 12 November and Calcutta 29 November. The route outlined was followed exactly to Darwin, reached 10 December at 3.40 p.m. From Rangoon to Singapore the monsoon rains gave them great trouble.

Third Day

	—Banjoewangie.
680	Koepang (Timor). (Here follows the only long oversea journey.)
500	Darwin.
250	Mataranka (inland, suggested capital, N.T.) .
1,430 miles.	

Fourth Day

	—Mataranka.
600	Cloncurry.
300	Longreach.
600	Brisbane.
1,500 miles.	

Fifth Day

	—Brisbane.
500	Sydney, or
600	to Canberra, or
900	to Melbourne.

Let us look more particularly into the meteorological factors on this route. It lies almost entirely in the monsoon and trade wind regions whose climates differ materially from those to which we are most of us accustomed.

The trade wind is a surface wind blowing from the south-east (over Australia) to the equator (see Fig. 218). Its limits vary during the year—for the belt is farther north in winter than in summer, moving with the sun. In our winter (July) these winds reach the equator, i.e. almost to Singapore, and will obviously hinder the aeroplane coming from India, but will help the return flight. In our summer (Fig. 217) their influence is not felt much north of the Tropics of Capricorn, and only the last day's journey from India will be affected. In the northern hemisphere the trade winds blowing from the north-east will be cross-winds in January and will be obliterated in July by the periodical monsoons.

The trade wind in north Queensland blows on an average about 20 miles per hour for weeks at a time, but it is probably less in other portions of its belt. This steady drift can obviously affect very considerably the velocity of the plane. This layer of the trade winds is, however, of limited thickness, for above it blows a poleward return wind. This is reached about 12,000 feet above sea level near the tropics (according to German data), but is lower in temperate regions. It is often reached in ascending 4,000 feet above Melbourne, and high regions like Kosciusko experience the west wind very frequently. We know nothing directly of its depth in our tropics.

These heights mentioned are quite those of the regular flight zones. Hence our air captain will doubtless fly from the equator to Southern Australia at high levels when the surface winds in July are against him, in this permanent anti-trade wind. At these elevations wind forces are much stronger, for there is little friction due to obstructions or turbulent eddies at heights above a mile. For instance, at the upper flight limit the winds in temperate latitudes have an average of about 60 miles per hour.

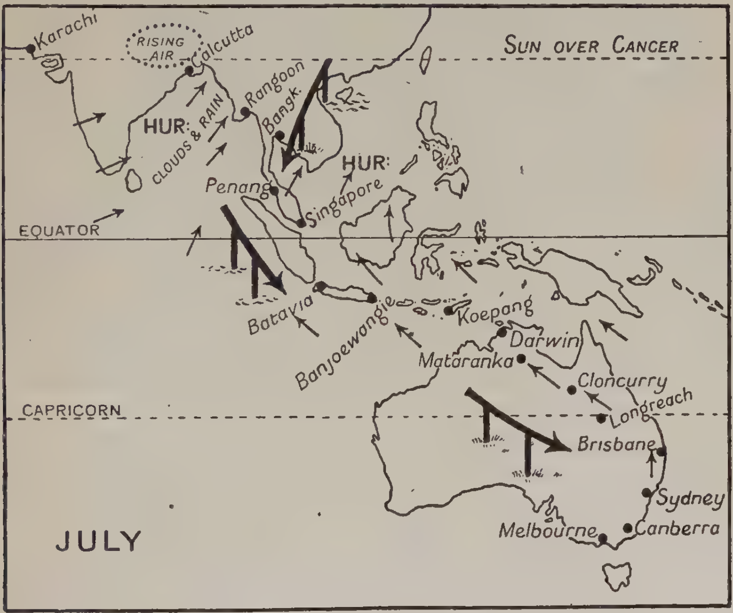

FIG. 218. The dominant winds in July. Those of the upper flying layer are on stilts.

During the summer seasons in the region discussed there is the maximum development of monsoons. The strong south-west monsoon of India blows during the hot months, and is accompanied by dense clouds, thunderstorms, and much rain. These winds are not favourable either in direction or in their accompanying meteorology for aviation. But here again they are confined to the lower 12,000 feet, and above this (as the Dutch have shown in Java) are found trade winds. The winter monsoon is practically the same as the trade wind.

In Australia the north-west monsoon blows in our northern regions during the three hottest months. It is a turbulent wind layer, and probably the aviator will prefer to fly above it, though the dominant monsoon wind from the north-west would help him to the south. Its extent and character can only be surmised at present.

Where the sun is vertically overhead the air is rising, and though these are calm regions at the surface, they are certainly turbulent areas in the flight zone. However, though heat-bumps on a large scale may be apparent, they have not much significance for a modern plane, and can be avoided by high flying.

The most violent storms of the tropics are the occasional hurricanes. Luckily these are confined to the oceans and rarely cause much damage far inland. They are prevalent in summer in the regions indicated, but aeroplanes flying overland will not often be dangerously affected. This is an unknown field of research, but one which it is unwise to postpone much longer.

The southern portion of Australia is dominated by anticyclones at the surface, and by the westward drift above. Here we are on more familiar ground. The anticyclones are surrounded by variable winds, generally unimportant from the present point of view. They have clear skies and afford good flying weather. The aviator will be interested in the more intense Lows (or cyclones) which periodically travel across southern Australia, but they are regularly forecasted and should not catch him unprepared for their clouds, rain, and strong winds.

Lieutenant-Colonel O'Gorman, in the last Wilbur Wright Memorial Lecture stated :

'Commercial aeronautics is bound up with using the [special] values which accrue . . . in the employment of aircraft. I take three of these : (*a*) Speed of transit. (*b*) Directness of route. (*c*) The utilization of helpful winds and evading bad weather.'

Much more might be written on this topic, but it is hoped that the reader will now realize how intimate is the connexion between meteorology and aviation, and also how much remains to be done in a scientific preparation for the forthcoming aerial traffic.

CHAPTER XXVI

CLIMATOLOGY

While climatology is so large a subject that it is usually treated separately from meteorology, yet the latter science forms the basis of climatology, and in its more economic aspects is hardly distinguishable from it. As Ward says:[1]

> 'When the term meteorology is used in its broadest meaning, climatology is a subdivision of meteorology. Climatology is largely descriptive. It aims to give as clear a picture as possible of the interaction of the various atmospheric phenomena at any place on the earth's surface. It rests upon physics and geography, the latter being a very prominent factor. Climatology may almost be defined as geographical meteorology. Its main object is to be of practical service to man.
>
> 'Climate and crops, climate and industry, climate and health, are subjects of vital interest to man. No other science concerns man more closely in his daily life.'

In this final chapter I shall merely give the salient features of Australian climatology. For details and arguments the reader is referred to the list of memoirs which is given at the end of the chapter.[2]

I have made free use of an article I contributed to the *Commonwealth Year Book* for 1918; where a lengthy *resumé* of all the main characteristics of the Australian climates may be consulted.

The Various Climates and their Analogues. There is a natural impression among Australians that the climate of our continent does not vary to any great extent from one end to the other. For Australia among all the large land masses has the least average elevation and the most unbroken coastline, and both of these conditions make for uniformity. But the area is very large and lies in one of the most variable climatic belts on the earth's surface; so that we shall be led into serious errors if we judge the Australian climate only by the southern types, with which alone some three-quarters of the inhabitants are familiar.

It will be useful for comparison to cross the world and glance for a moment at the better appreciated diversity of climates in the region lying between Ireland and India. Facing the almost permanent westerly gales is the rugged west coast of Ireland. It receives a perpetual drenching from the moisture laden winds, and the result is that western Ireland has large areas of bogland and of much deciduous forests, but is too wet for cereals. Similar conditions obtain in western Tasmania (see Fig. 219).

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[1] *Climate*, by Professor R. De Courcy Ward. London, 1910.

[2] Rainfall and Temperature data for typical Australian regions appear in the Appendix.

Passing farther to the south-east we reach the Mediterranean lands. Here is an absence of deciduous trees, their place being taken largely by evergreens. A sharply marked seasonal rainfall is experienced, with considerable periods of drought. We have the same features in most of southern Australia. Passing south of the Mediterranean we approach the desert regions of the Sahara. They are bordered by a grassland belt watered by scanty winter rains, and closely agree with the region of the new East–West railway. To the east of the Mediterranean and somewhat remote from the sea are the steppes of the Caspian. These are to some extent paralleled by the Riverina—though the latter is warmer.

The true desert of Sahara, with a rainfall below 5 or 6 inches, is represented by the region around Lake Eyre, and perhaps in Western Australia. Approaching the equator we come to savanna regions, which are grass lands watered by scanty summer rain. Such is the Sudan, and it is represented in Australia by the inland regions along our tropic.

Our survey has now reached the tropical regions of India, which have a good monsoon rainfall. Here we should differentiate between the centre of the peninsula, with a well-marked winter drought, and the east coast. The former agrees with northern Australia, while the Madras coast resembles the north Queensland coast with a much heavier and more uniform rainfall.

In addition to the eight climatic regions already noted, there is a special type along the coast of New South Wales which differs considerably from any so far touched upon. Its homoclimes are in China and Brazil.

It would be quite proper to include Papua and Macquarie Island in our survey of the climate of the Commonwealth. Macquarie Island lies in 55° S. latitude to the south of Tasmania, and its climate resembles that of Iceland.

Hence we could extend our scale through the whole of tropical, temperate, and sub-polar climates.

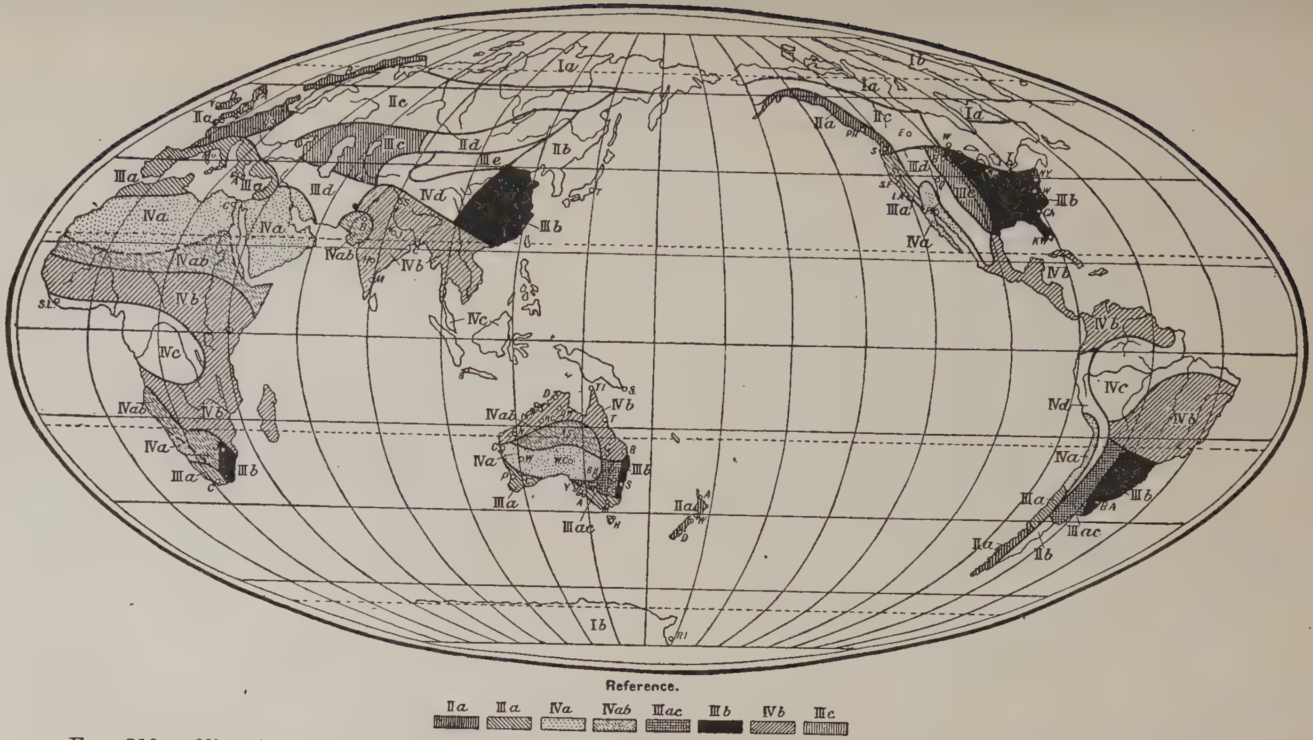

FIG. 219. Climatic regions of the world (modified from Herbertson). Those akin to Australian climates are shaded. I*a*—Tundra. I*b*—Ice-cap. II*a*—West European type. II*b*—Quebec type. II*c*—Siberian type. II*d*—Rockies type. III*a*—Mediterranean type. III*ac*—Murray basin type. III*b*—Warm eastern margin. III*c*—Warm interior lowlands. III*d*—Warm plateau. IV*a*—West tropical arid region (some winter rain). IV*ab*—West tropical arid region (some summer rain). IV*b*—Monsoon and Sudan type. IV*c*—Equatorial lowlands. IV*d*—Hot plateau.

There can be little doubt that climate is the major factor in determining the permanent settlement of the various regions of the earth. It controls agriculture and grazing, which in their turn largely determine manufacturing industries. It controls comfort and health—very potent factors in the spread of white civilizations. In fact, were it not for certain valuable mineral deposits, one would find that practically all the main centres of white settlement could be defined in terms of temperature, humidity, and rainfall.

Similar controls no doubt operate in connexion with the other races. Probably the black race flourishes within narrower limits, and the yellow race within wider limits than the white race ; but a very short survey will show that the Australian Commonwealth contains regions akin to those inhabited by types of each of the great races of mankind.

Thus we have in Australia climatic factors such as are associated with all the following peoples and products :

Nordic races as in parts of Ireland—tall, fair-haired men interested in pigs, potatoes, and peat. Shorter Alpine ' roundheads ', as in Central France, concerned with sheep and cattle. Short dark Mediterranean people, as in Italy, busy with wheat, olives, and wine. In the irrigated districts in Egypt are the Copts, growing rice and cotton ; while in the drier regions nearby are the Syrians, concerned *inter alia* with tobacco and goats. In the true desert is the Tuareg, whose environment has made him a nomad. Belonging also to the white race are the Hindus of the north of India, who grow cotton, rice, jute, and oilseed.

The yellow Kirghiz of the Caspian steppes are pastoral nomads whose southern lands are becoming important cotton areas. Corresponding to the New South Wales coast we have eastern China with tea, maize, and sugar-cane grown by pure Mongolians.

The savannas of the Sudan are peopled by negroes interested in cattle, millet, and various gums. The south of India, containing dark Dravidians of doubtful origin, produces coffee, tea, and tropical oilseed.

Here, indeed, is a ' diversity of creatures ', whose whole scheme of life is largely determined by their environment. In Australia the environment is as diverse, and it is logical to assume that it will exert a potent if slow and hidden influence on Australians.

Control by Temperature. Early in the study of climatology it was discovered that the southern hemisphere is cooler than the northern. This fact has been taken by many people to imply that tropical Australia is much cooler than similarly situated regions in other continents. Moreover, they often proceed to state that the *heat* equator is confined to the northern hemisphere, and hence that only a mere coastal fringe along our north coast can properly be assigned to tropical Australia.

The above general statements are true—but the deductions are wrong, for the reason that Australia is an exception to both rules. There is no mysterious virtue about the southern hemisphere—it is merely the great preponderance of ocean which keeps its average temperature low. But the few large land masses—of which Australia is one—are hot enough, as it is only too easy to show.

Table 1. Latitude and Temperature

	Average Temperature.		*Temperature in Australian Regions.*	
Lat.	*North Hem.*	*South Hem.*	*Along* 135° *E. Long.*	
0°	78·5° F.	78·5° F.	80° F.	Tropic.
5°	79·0° F.	77·9° F.	80· F.	
10°	79·5° F.	77·0° F.	82° F.	
15°	79·4° F.	75·7° F.	81° F.	
20°	78·0° F.	73·0° F.	76° F.	
25°	74·7° F.	69·7° F.	70° F.	Temperate.
30°	68·5° F.	65·4° F.	66° F.	
35°	63·0° F.	59·4° F.	61° F.	
40°	57·2° F.	53·2° F.	55° F.	

(N.B. The last column shows smoothed temperatures along longitude 135° E., which fairly represent the 'continental' portion of Australia.)

Hence we see that tropical Australia is not only hotter than the average for the southern hemisphere, but is hotter than the average for the northern hemisphere. It is, indeed, much hotter than any land between us and the North Pole. It is, therefore, obvious that the heat equator must be drawn through northern Australia (see Figs. 91 and 50).

There are two further reasons why Australian climates have not been properly estimated in the past.

Almost all maps showing world temperatures are so constructed that the effect of elevation is removed by reducing the temperature readings to sea level. Thus authoritative maps show the city of Mexico with an average annual temperature of 80° F.; much the same as Broome in the same latitude.

But actually the average temperature of Mexico is under 60° F.; and the same applies to many other tropical areas. As we shall see, no other continent has so large a proportion of lowlands.

Furthermore, if we tabulate those localities having an average annual temperature over 84° F., we find that there are only four such regions of greatest heat recorded in the authoritative work by Hann. These are:

TABLE 2. HOTTEST REGIONS OF THE GLOBE

Region.	*Average Temperature.*	*Average Rainfall.*
1. Timbuktu and vicinity . .	84° F.	0–10 inches.
2. Massowah to Khartum . .	86° F.	10–20 ,,
3. Tinnevelli in South India . . .	84·3° F.	40–60 ,,
4. Wyndham in north-west Australia	84·4° F.	40–60 ,,

If we consider the moistness of the heat, we see that Wyndham has an unenviable position among the world's climates—at any rate in the rainy season. (Fig. 50.)

THE EFFECT OF ELEVATION. Large portions of the British tropical areas are luckily situated at high altitudes. Thus in Rhodesia approximately 90 per cent. (some 400,000 square miles) is over 2,000 feet above sea level. This lowers the temperature by about 7° F., and is a vital factor in regard to settlement. Let us see how the elevation affects settlement in Australia.

In the tropics there are only three areas which are worth considering.

TABLE 3. TROPICAL HIGHLANDS

Tropical Highlands.[1]	*Approximate Area over 2,000 feet. Sq. Miles.*	*Per cent. of State.*
A. Atherton Tableland, Queensland . .	12,000	2·0
B. Macdonnell Ranges, North Territory .	14,000	2·6
C. Fortescue River Area, West Australia .	11,000	1·0

Adding a few much smaller areas we find that only 4 per cent. of tropical Australia is high enough to benefit in this respect. The result is that we shall be doing Australia no injustice if we take the tropic of Capricorn as truly representing the southern limit of the tropics of Australia.

As regards temperate Australia there are but few noteworthy features in the distribution of temperature. Only in the east and south-east are the settled highlands extensive enough to be important.

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[1] In Tables 3, 4, and 5 the index letters correspond with those on Fig. 220.

The following tables give approximate areas for the *temperate* regions above 2,000 feet in eastern Australia. These all have an adequate rainfall.

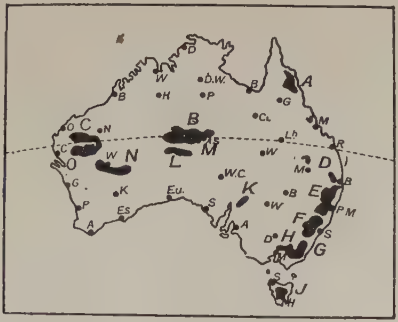

FIG. 220. Highlands approximately over 2,000 feet.

TABLE 4. EASTERN TEMPERATE HIGHLANDS

Well-watered Highlands.[1]	*Approximate Area over 2,000 feet. Sq. Miles.*	*Rainfall. Inches.*
D. Darling Downs and Tambo Downs (Queensland)	2,300	30
E. New England Plateau (N.S.W.) including Macpherson Ranges . . .	23,500	35
F. Blue Mountain Plateau (N.S.W.) . .	14,800	30
G. Monaro Plateau (N.S.W.) . . .	13,300	25
H. Victorian Highlands (Victoria) . .	7,700	50
J. Tasmanian Highlands	4,400	40
	66,000	

Of less important temperate highlands—all situated in regions of low rainfall—there are several in other states.

TABLE 5. DRY TEMPERATE HIGHLANDS

Dry Highlands.[1]	*Approximate Area. Sq. Miles.*	*Estimated Rainfall. Inches.*
K. Flinders Range, South Australia .	1,360	10
L. Musgrave Ranges, South Australia .	6,300	10
M. Macdonnells (temperate), Northern Territory	7,600	9
N. Wiluna Highlands, West Australia .	11,600	9
O. Ashburton Highlands, West Australia	21,200	9
	48,000	

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[1] In Tables 3, 4, and 5 the index letters correspond with those on Fig. 220.

There are a few small areas such as the Stirling Range (W.A.) which average less than one thousand square miles each, so that we may sum up the total highland areas of Australia as follows:

TABLE 6. AUSTRALIAN HIGHLANDS, OVER 2,000 FEET

	Sq. Miles.	
Tropical Dry	25,000	40,000
Tropical Wet	15,000	
Temperate Dry	48,000	114,000
Temperate Wet	66,000	
Total		154,000

—which is a very small proportion (about 5 per cent.) of the total area of the Commonwealth.[1]

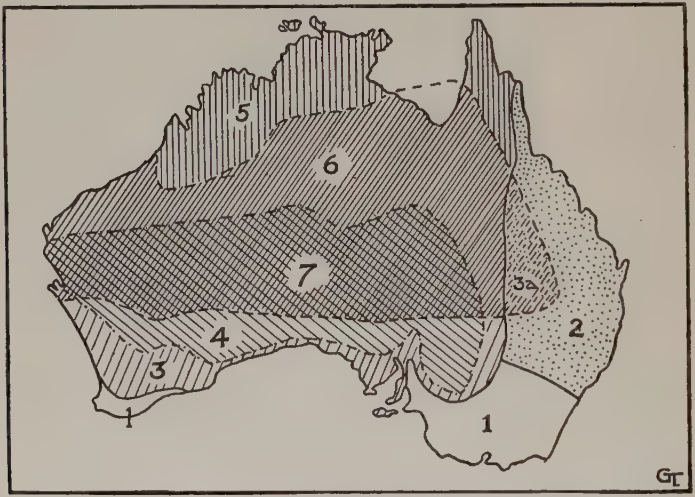

FIG. 221. Economic rainfall regions. 1 and 2 have uniform and reliable rain. 3, 4, and 5 have seasonal and reliable rain. 3*a*, 6, and 7 have erratic rainfall. (See Table on p. 287.)

Range of Temperature, Relative Humidity, Rainfall Distribution, and Rain Reliability are all discussed and illustrated in Chapters VI, XII, and XIV–XVI, to which the reader is referred.

RAIN REGIONS. The chief climatic control in Australia is the rainfall. Hence our sub-division of Australia into type climatic regions must primarily be based on this element. In Fig. 113 the arid region (below 10 inches a year) is defined. In Fig. 118 the region characterized by an erratic rainfall is indicated, and in Fig. 120 that benefited with a uniform rainfall. The boundary between the winter and summer rainfall regions has been discussed in several sections, e.g. Fig. 119.

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[1] The topographic control of rainfall in East Australia is treated more fully in Appendix 1.

I have combined these varied characters into a practical regional map in Fig. 221. Here the variations of the rainfall in amount, in season, in uniformity, and in reliability are all used as criteria. (See also Fig. 228.)

The seven regions may be arranged in order of their value for settlement somewhat as follows (Mining is ignored):

Class.	*Sub-Class.*	*Chief Localities.*	*Chief Products.*
1. Uniform.	With winter maximum.	Riverina; Victoria; Tasmania; Albany.	Timber, dairies, farming, sheep, wheat, vines.
2. ,,	With summer maximum.	Eastern Queensland,[1] north-east of New South Wales.	Farms, sheep, cattle; also timber, dairies, and sugar on coast.
3. Seasonal but reliable.	Moderate winter type.	Swanland[2] (W.A.)	Wheat, sheep, vines.
4. ,,	Arid winter type.	Coolgardie to Broken Hill.	Sheep.
5. ,,	Summer type.	Kimberley, W.A., and Coastlands, N.T.	Cattle.
6. Erratic.	Summer only.	Pilbarra, W.A., Macdonnells, N.T., Western Queensland.	Sheep and cattle.
7. ,,	Arid.	Central W.A. and Inland S.A.	Unoccupied except for a few sheep and cattle stations.

Climate and Production. In *Bulletin* 11, published at the Melbourne Weather Bureau, the controls governing our chief primary industries, sheep, cattle, and wheat, have been investigated. The conclusions are somewhat as follows, and very well illustrate the economic aspect of the study.

Cattle. By far the greater number of cattle are reared in the eastern coastal belt. In the three eastern States the cattle occur almost wholly in the wetter region outside the 20-inch isohyet. The chief advance will be made in Kimberley (W.A.) and in Northern Territory. This can be seen from Fig. 222.

The large empty spaces in central Queensland and western New South Wales are already occupied by sheep, and the latter will probably displace cattle in most of the cooler sparsely occupied portions of the continent.

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[1] The region 3a has too erratic a rainfall to be classed with 2.

[2] The temperate and well-watered south-west corner of West Australia.

The following table (mainly based on data given by Messrs. Knibbs and Hunt) shows at a glance the relative importance of the States, and the proportions of cattle reared for dairy purposes. The areas of well watered country on which both the future beef and present dairy industries depend are shown in the middle columns.

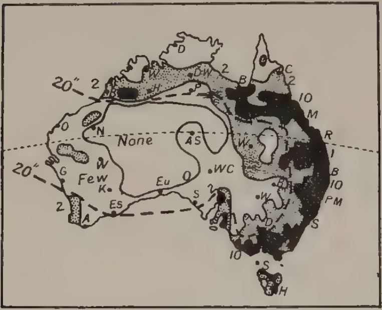

Fig. 222. The control of the cattle industry by the rainfall. All the chief areas receive more than 20 inches per annum. Black areas have more than 10 cattle per square mile. Dotted areas have more than two.

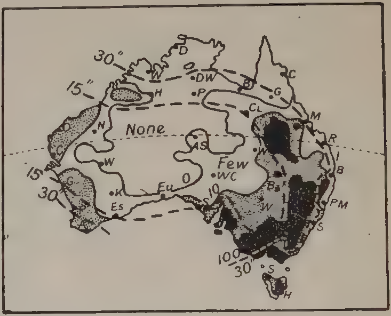

Fig. 223. The control of the sheep industry by the 15- and 30-inch isohyets. Black areas over 100 sheep per square mile. Dotted areas over 10.

Cattle and Rainfall in Australia

	Cattle.	Per cent. of Australia.	Area over 20 inches in Square Miles. Tropical.	Area over 20 inches in Square Miles. Temperate.	Dairy Cattle.	Per cent. in State.
Queensland . .	5,210,891	45·0	313,183	80,000	375,660	7·2
New South Wales	[1] 3,033,726	26·2	—	130,468	852,040	28·0
Victoria . .	1,508,089	13·0	—	55,346	655,939	44·0
Western Australia	806,294	7·0	102,606	36,924	27,310	3·0
Northern Territory	405,552	3·5	180,940	—	300	·07
South Australia .	383,418	3·3	—	14,875	114,734	33·6
Tasmania . .	222,181	2·0	—	25,278	60,160	27·0
Total[2] . .	11,577,259	100·0	—	—	2,086,885	—

In Fig. 223 the distribution of sheep throughout the Commonwealth is charted from the more detailed State maps given in my memoir. The black areas represent more important regions, just as in the preceding cattle map (Fig. 222). It is interesting to compare the characters of these two maps. The sheep occupy the warm inland drier belt and the cattle the wetter coastal regions. In general, an important sheep country is not noted for cattle, and vice versa; but in New England (New South Wales) and the west-central portion of Victoria the two industries are intermingled.

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[1] Plus 7,108 in Federal Capital Territory.

[2] Data for 1912. In 1916 slightly less.

The best rainfall for sheep in the Queensland tropics is seen to be from 15 to 20 inches. There is a considerable area in Western Australia along the Pearling Coast with this rainfall, and it is indeed already sparsely occupied by sheep. The region in the south-west of Western Australia ('Swanland') is analogous in climate and situation to the important sheep country of New South Wales. Hence the chief developments of the future should logically lie in Western Australia, with the result that the present sparsely grazed areas will be converted in the near future into closely stocked regions. An extension of the sparsely stocked region (ten-sheep isopleth) to the 10-inch isohyet near Kalgoorlie is also to be expected.

			Rain Control.	
	Number of Sheep.	*Per cent. of Australia.*	*Optimum Belt. Inches.*	*Total Belt. Inches.*
1. New South Wales	38,855,861	46·7	20 to 30	10 to 40
2. Queensland	20,310,036	24·4	15 to 20	10 to 30
3. Victoria	11,892,224	14·3	20 ,, 30	10 ,, 50
4. South Australia	5,481,489	6·6	20 ,, 30	5 ,, 30
5. Western Australia	4,596,958	5·5	20 ,, 30	8 ,, 40
6. Tasmania	1,862,669	2·2	20 ,, 30	20 ,, 60
7. Northern Territory	75,808	·1	—	10 ,, 20
8. Federal Territory	188,641	·2		
Total[1]	83,263,686	100·0		

WHEAT. The Commonwealth meteorologist has published maps showing the rainfall during the chief growing period (April to October). In *Bulletin* 11 these areas are compared with the actual distribution of the wheat crops, and the relation is shown to be very close.

The northern limit of wheat is determined largely by temperature. The isotherms are shown in Fig. 224. The most northern wheat on a large scale is grown along the railway to Roma (in Queensland).

A consideration of climatic controls in U.S.A. (especially Texas) and in northern India seems to indicate a considerable extension of Queensland wheat, which is shown on Fig. 224.

[1] Data for 1912. In 1916 slightly less.

The isotherms run approximately east and west, but curve around two cold areas in the south-west and south-east corners of the continent respectively.

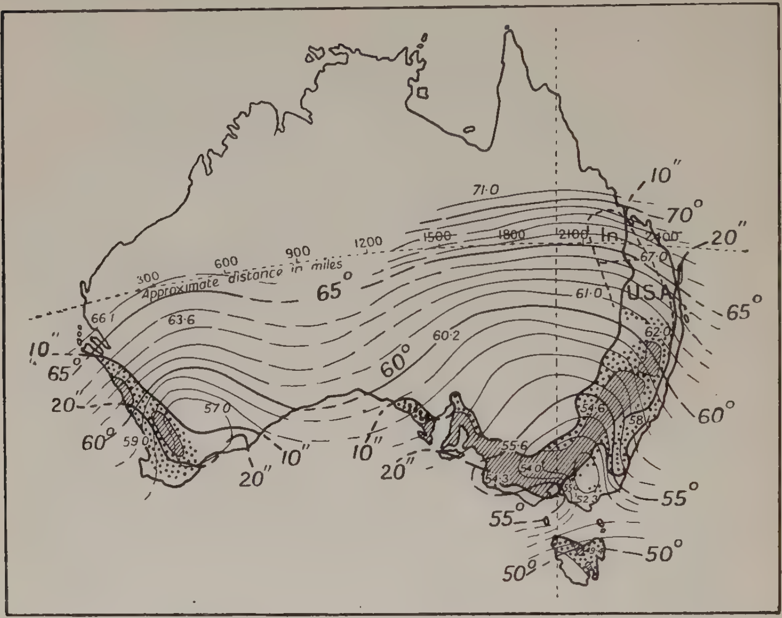

FIG. 224. The climatic control of wheat production. (The 10-inch and 20-inch winter rainfall (April–October) is based on H. A. Hunt.) The average temperature during the same period is given. Regions of heavy wheat production are ruled; of light production are dotted. Analogues with Indian and U.S.A. wheatfields are indicated in Queensland.

With the aid of this map it is possible to tabulate the climatic controls governing wheat culture in the various states :

Wheat Belt.	*Temperature.*			*Rainfall.*		
	Annual.	*April–October.*		*Annual.*	*April–October.*	
		Whole Area.	*Best Area.*	*Inches.*	*Whole Area.* *Inches.*	*Best Are* *Inches.*
Western Australia	70°–60°	63°–57°	62°–57°	40–10	30–10	20–15
South Australia	67°–58°	58°–54°	57°–55°	30–10	25–6	20–10
Queensland	68°–65°	60°–62°	—	40–23	20–10	—
New South Wales	67°–56°	61°–52°	61°–52°	45–14	25–9	15–11
Victoria	63°–55°	55°–52°	55°–52°	40–12	25–8	15–10
Tasmania	56°–50°	52°–46°	—	60–19	40–10	25–10

In the preceding sections I have drawn attention to the regions which are climatically suited for wheat, but are not yet exploited. These are the region north-east of Albany (in Western Australia), the northern portions of Eyre's Peninsula (in South Australia), the northern fringe of the wheat area of New South Wales from Coonamble to the Queensland border, and, finally, the south-east portion of Queensland. All except the latter region are normal extensions of well-known wheat areas.

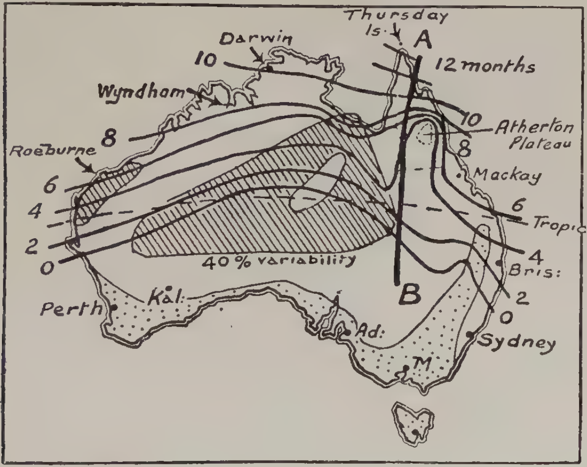

Fig. 225. Climatic control of settlement.

Wet-bulb Temperatures and Comfort. It is generally accepted by physiologists that the best available instrument for testing the suitability of a region as regards habitability is the wet-bulb thermometer. Professor J. W. Gregory quotes 78° F. wet bulb as an upward limit—'above which continuous hard work becomes impracticable.' Unfortunately for Australia 78° F. wet bulb is quite common in summer along our northern coast, but this statement (by a strong supporter of tropical white settlement) will free the following deductions from a charge of exaggeration.

For reasons which are elaborated in *Meteorological Bulletin* No. 14,[1] 70° F. (wet bulb) has been adopted as the limit of comfort for our race. This means that when the average wet bulb remains

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[1] See list at end of chapter.

70° F. day after day for a long period, conditions are not favourable for close white settlement. An open-air active occupation such as stock-riding has little to fear; but strenuous field labour, sedentary indoor life, and especially domestic work and the care of young children, cannot be carried on under favourable conditions at present with high wet-bulb temperature of this order.

It is well known that February is usually the most oppressive month both in Sydney and Melbourne. The average wet-bulb temperatures for this month are, however, only 65° F. and 60° respectively, while at Melbourne the *extreme* reading for any day in the year rarely exceeds 75° F.

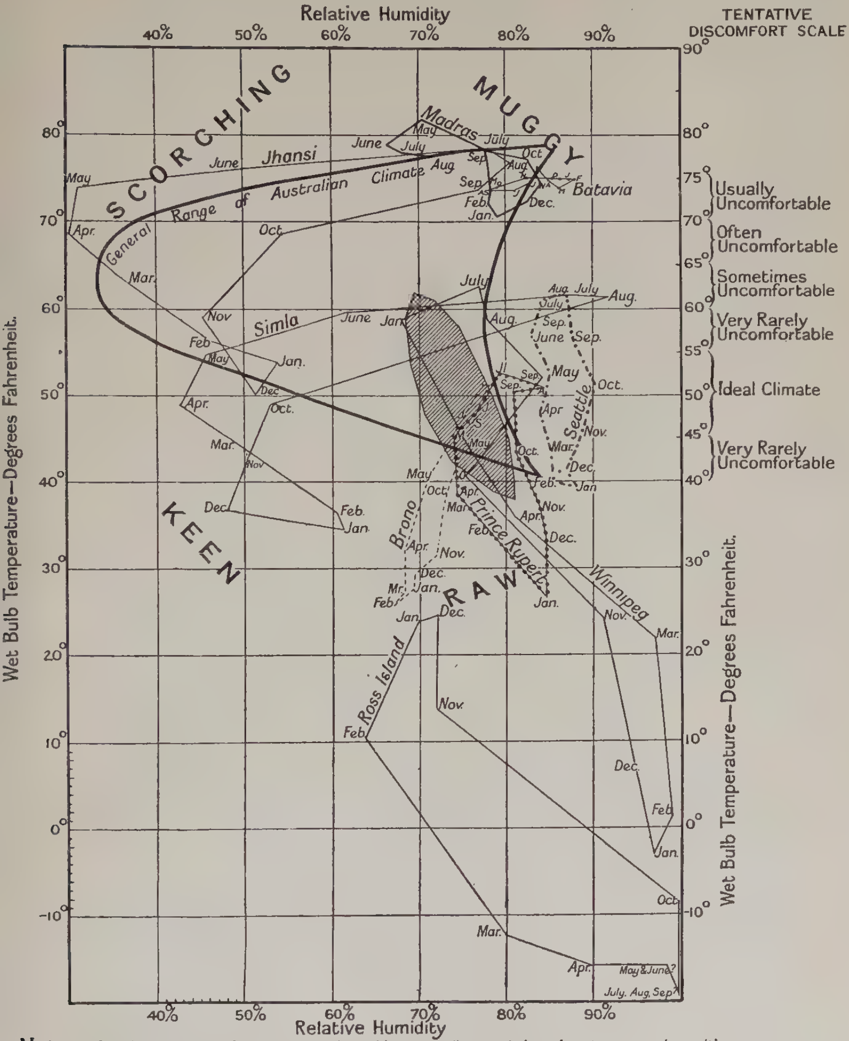
Brisbane has two months with an *average* wet bulb over 70° F., and conditions become continuously less attractive as we journey up the coast. At Mackay such high wet bulbs obtain for six months in the year; at Cooktown for ten; and at Thursday Island all the year round. These isopleths are plotted on Fig. 225. It will be noticed that it is precisely the low-lying river alluvials of the north which are adversely affected. Here irrigation may ultimately be possible, for there are many truly fine rivers running into our northern seas. But it is doubtful if a white farming community will settle in these suitable areas for very many years.

THE CLIMOGRAPH. *Bulletin* 14 described a graphic method of comparing climates which may be briefly repeated here, as I have referred to the climographs in some of the following regional sections:

> With wet-bulb temperatures as ordinates and relative humidities as abscissae the twelve average monthly figures are plotted for the locality required. Thus a twelve-sided polygon (the climograph) is obtained. This extends toward one of the four corners of the chart according as the climate approximates to muggy, scorching, keen, or raw conditions. A scale of discomfort based on wet-bulb conditions is appended at the side. A composite climograph based on averages from twelve large white cities is inserted, and serves as a standard of comparison.

In Fig. 226 are shown types of all the chief climates of the world, while at the side is a tentative scale of discomfort depending on the wet-bulb readings alone.

As a criterion enabling one to judge if a locality is well suited for close white settlement, a composite climograph is given, based on averages from twelve centres of Anglo-Saxon settlement. This is the cigar-shaped climograph, which is shaded in Fig. 226.



Note.—*The shaded figure is the composite white race climograph based on twelve typical cities.*

FIG. 226. Characteristic climographs illustrating important climatic types.

Unhealthy regions near the equator with a uniformly muggy climate are represented by Madras and Batavia. Scorching dry regions—with, however, monsoon rains in midsummer—are illustrated by Jhansi in Central India. Simla shows one of the keen winter types, though it is also affected by the monsoons in summer. London (see Fig. 227) agrees almost exactly with the composite climograph. Seattle (U.S.A.) is similar, but wetter. Brono (near Trondhjem) and Prince Rupert (B.C.) illustrate raw conditions. Winnipeg and Ross Island (Antarctica) extend far below the temperatures of normal white settlement.

In Fig. 227 is given a chart reproducing typical climographs for the whole of Australia. The graphs cover a conical area,[1] where the right hand shows the moist coastal towns ; and the left hand the arid towns. For other continents where the range is greater the area covered is proportionately larger. Those climographs in the lower right corner are best suited to close white settlement, for they approach nearest to the ‘ composite climograph ’. The latter is based on Sydney, Perth, Hobart, Capetown, Johannesburg, London, Aberdeen, Berlin, Toronto, New York, Chicago, and Seattle. London and Berlin are added separately for comparison in Fig. 227.

The chart shows that four types of climate are included. The somewhat muggy, trying climates of the *north coast* have elongated climographs sloping from the centre to the muggy corner. The slope shows that they belong to the monsoon types with wet summers and dry winters.

The *dry central* districts of Australia have crescentic climographs, in the left half of the chart. This crescentic shape shows that they are affected both by summer and winter rains.

The cooler southern towns have elongated climographs sloping from the centre to the raw quadrant. This slope shows that they belong to the *winter-rain* region.

The *east coast towns* like Sydney and Brisbane have wide oval climographs, showing that all four seasons differ materially in character, whereas in the other three groups the spring and autumn conditions are much the same.

Hence the shape of the climograph is characteristic, and with a little practice can readily be recognized.

The climates represented in Australia are naturally somewhat restricted. Their limits are shown in Fig. 226 by the heavy boundary (like an arrow-head).

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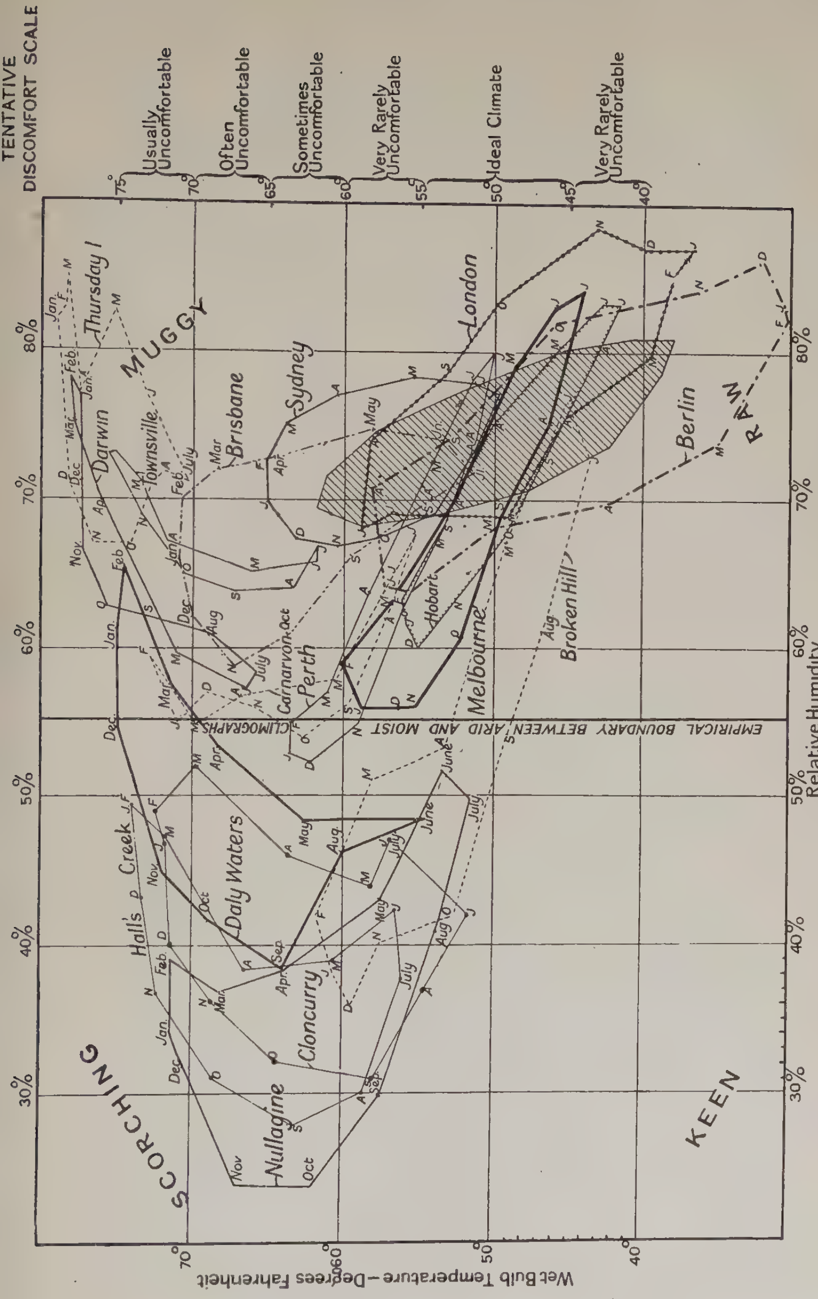
[1] This is shown by the heavy black line on Fig. 226.



Note *The shaded figure is the composite white race climograph based on twelve typical cities.*

FIG. 227. Typical climographs for Australia (London and Berlin added for comparison).

The Tentative Scale of Discomfort at the side of the chart will enable the reader to see the conditions in any month at any of the localities at a glance. He can also compare the localities *inter se*; and by reference to the original memoir (*Bulletin* 14, where seventy climographs are charted) with most other regions of the world.

Settlement in the Tropics. The chief object of this chapter is to focus attention on the climatic difficulties which hinder settlement in the unoccupied regions of Australia. Space does not permit of the insertion of further illustrative climographs, but the table on the opposite page indicates quite clearly that our northern lands are not well suited for *close* white settlement. In the table the foreign *homoclime* (similar region) appears in each case at the right of the Australian locality (see Figs. 219 and 228).

Assuming that these and similar parallels are correct, we see that the analogous regions (homoclimes) for Darwin are settled by Siamese, Indians, and Bantu blacks, and in northern Brazil by half-caste Portuguese. Wyndham (as I stated earlier) has for homoclime only the extreme tip of India. Broome's homoclime is settled by Bantu. Townsville is paralleled by Rio de Janeiro, which is settled by the Portuguese.

Only in the inland country like that around Wiluna or Daly Waters have we a homoclime even sparsely settled by north Europeans. This is the recently conquered German territory of South-West Africa.

In eastern Brazil is a most interesting series of settlements: but the Germans have settled in the homoclime of Grafton; the Italians in Brazilian ‘Brisbane’, and only the Spanish touch even the cooler tropical regions.

This brief but comprehensive climatological study shows that Australia is ahead in tropical settlement. Her white sugar-growers around Cairns and Mourilyan are the advance-guard of the white farmer in the tropics.

I have no space to do more than mention one great asset in our northern lands—their remarkable freedom from such scourges as yellow fever, beri-beri, and malaria. There seems good reason to hope that even the latter will soon be almost stamped out.

What then is indicated as regards the immediate future of our empty northern lands? The country is clearly a pastoral

AUSTRALIAN HOMOCLIMES

AUSTRALIAN LOCALITY[1] AND ITS FOREIGN HOMOCLIME

Australian Locality.	Temperature. Average.	Temperature. Hottest. Month.	Temperature. Coldest Month.	Rainfall. Average.	Rainfall. Wettest Month.	Rainfall. Driest Month.	Foreign Locality.	Temperature. Average.	Temperature. Hottest Month.	Temperature. Coldest Month.	Rainfall. Average.	Rainfall. Wettest Month.	Rainfall. Driest Month.
	Deg. F.			Inches.	Inches.			Deg. F.			Inches.	Inches.	
A. Broome .	79·8	85·9	70·3	23	6	0	A. Banana (R. Congo)	77·9	81·5	72·5	29	6	0
B. Nullagine .	79·8	85·9	70·3	23	3	0	B. Colima (Mexico)	76·1	80·0	69·6	34	7	0
C. Carnarvon .	71·0	80·0	60·0	9	3	0	C. Olukonda (SW. Africa)	72·0	77·0	51·0	19	5	0
D. Wiluna .	70·0	85·0	52·0	10	2	0	D. Windhoek (SW. Africa)	67·0	74·0	56·0	15	4	0
E. Darwin .	83·0	84·0	77·0	62	15	0	E. Cuttack (E. of India)	80·0	87·0	70·0	55	12	0
F. Daly Waters	80·0	87·0	69·0	27	6	0	F. Quixeramobim (Brazil)	81·0	83·0	79·0	27	6	0
G. Alice Springs	70·0	84·0	53·0	11	2	0	G. Biskra (Algeria)	69·0	89·0	51·0	10	1	0
H. Townsville .	78·0	82·0	66·0	49	11	0	H. Calcutta	78·0	82·0	65·0	60	12	0
I. Wyndham .	84·5	88·3	76·2	27	8	0	I. Tinnevelli	84·3	89·5	78·5	28	9	0
J. Perth .	64·0	73·6	55·0	33	6	0	J. Capetown	61·3	69·2	54·2	24	3	0
K. Brisbane .	68·8	77·2	58·0	47	7	2	K. Durban	70·7	77·0	64·2	42	6	1
L. Sydney .	63·0	71·6	52·3	48	5	3	L. Wilmington	62·2	78·6	45·7	42	4	2
M. Melbourne .	58·3	67·5	48·4	26	3	2	M. Oporto	57·4	67·3	47·5	48	6	1
N. Launceston	54·8	64·5	44·1	28	3	1	N. Falmouth	52·4	62·7	42·4	41	7	2

---

[1] These localities are shown on Fig. 229.

one—it is not an agricultural region. Quite apart from questions of labour and market, the northern agricultural areas are not suitable for white farming at present.

A consideration of progress in Algeria and similar regions indicates that conditions in our tropics may become more acceptable to white settlers in the future. In four or five generations it is possible that our native-born may become thoroughly acclimatized in the sub-tropical areas, and will then gradually expand in considerable numbers into the hotter and more humid zone to the north.

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6. *Climatic Factors in Australia*, 1918. *Commonwealth Year-Book*, Melbourne.
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9. *Climate and Crops of Commonwealth.* (In the Press.)
10. *The Fringe of the Australian Desert.* (In the Press.)
11. *Future White Settlement of the World.* (In the Press.)

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[1] A fairly complete bibliography of kindred Australian literature appears at the end of this memoir.

[2] Republished by the American Geographical Society, August 1919.

APPENDICES I AND II

APPENDIX I

TOPOGRAPHIC CONTROL OF RAIN IN S.E. AUSTRALIA

A MORE extended notice may be devoted to the south-east corner of Australia, where, in only 15 per cent. of the total area, no less than 85 per cent. of the population of the continent dwells. Here the contours have been very approximately charted, and the occurrence of alternating areas of a drier and wetter type than normal is a very interesting and marked feature. In the map shown on Fig. 228, it will be noticed that the so-called Dividing Range in the south consists really of five more or less disconnected 'massifs'. In the north is the largest of all—the New England Plateau. Then a broad low gap (near Cassilis), of much physiographic importance, and hence conveniently named a 'Gate', separates the first massif from the Blue Mountain massif. Another 'Gate' around Lake George is the northern boundary of two well-marked mountain areas. These latter—the Snowy (on the west)

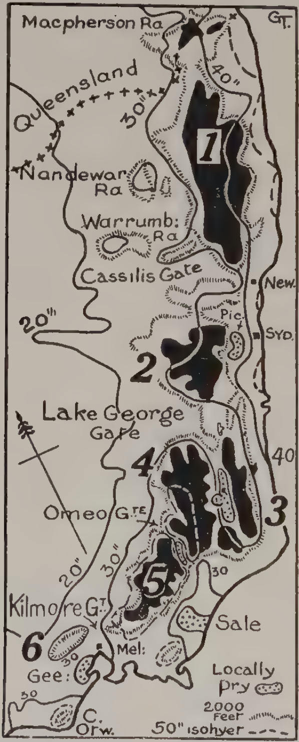

FIG. 228. The topographic control of rainfall in South-East Australia. Regions 1–5, over 3,000 ft. are black (see Table). 6. Cooma in the Rift Valley.

and Tindery Ranges (on the east)—are separated by a long north-south fault valley, or subsidence area, which has been named the Australian Rift Valley, with its summit at the Cooma Gate.

The Snowy Mountains continue as the Bowen Mountains in Victoria, and are separated from the more eastern massif (the Barry Mountains) by the Omeo Gate. At Kilmore the cordillera practically finishes, though a well-marked low plateau near Ballarat prolongs the main divide to the westward.

If we now consider the distribution of rainfall, we shall recognize how closely it is bound up with this alternation of Highland and 'Gate'.

This is perhaps shown most graphically in a table:

	Name.	*Number on Map.*	*Height.*	*Rainfall.*
Wet	New England Plateau	(1)	3,000 ft. +	30–40 in.
Dry	Cassilis Gate		1,000–2,000 ft.	20–30 in.
Wet	Blue Mountain area	(2)	3,000 ft. +	30–40 in.
Dry	Lake George Gate		2,000 ft.	20–25 in.
Wet	Tindery Range	(3)	3,000–5,000 ft.	25–30 in.
Dry	Cooma Gate		2,000–3,000 ft.	Under 20 in.
Wet	Snowy Ranges	(4)	3,000–7,000 ft.	Over 50 in.
Dry	Omeo Gate		2,000–3,000 ft.	20–30 in.
Wet	Barry Mountains	(5)	3,000–5,000 ft.	Over 50 in.
Dry	Kilmore Gate		1,200 ft.	25 in.
Wet	Ballarat Uplands	(6)	2,000 ft.	30 in.

One or two other isolated areas deserve brief mention. The noticeable effect of the comparatively low Cape Otway Ranges on the rainfall is very evident. The latter, though less than 2,000 ft. high, lead to precipitations of over 50 in. annually. Near Geelong is one of the peculiar *locally dry* areas, due no doubt to its occupying a low-lying situation, sheltered from north, south, and north-west winds.

A similar occurrence of heavy rainfall (50 in.) on the Gippsland Hills (1,000–2,000 ft.) seems to have robbed the atmosphere of the moisture due to the more eastern regions around Sale. The latter has 5 in. less rainfall than the rest of Eastern Victoria, and lies in a well-marked rain-shadow.

We have noticed the dry belt in the Omeo region, and the similar but larger dry belt in the Cooma Valley. Behind Sydney is a very interesting patch extending from Picton to the Emu Plains, with less than 30 in. This area lies between the Blue Mountains and the highlands about Bowral and Moss Vale. The former intercept the westerly rains, the latter those coming from the south-east.

The volcanic ranges of the Warrumbungles and Nandewars also give rise to considerable increase in the rainfall in the vicinity.

APPENDIX II

TEMPERATURE AND RAINFALL AVERAGES FOR AUSTRALIAN TOWNS

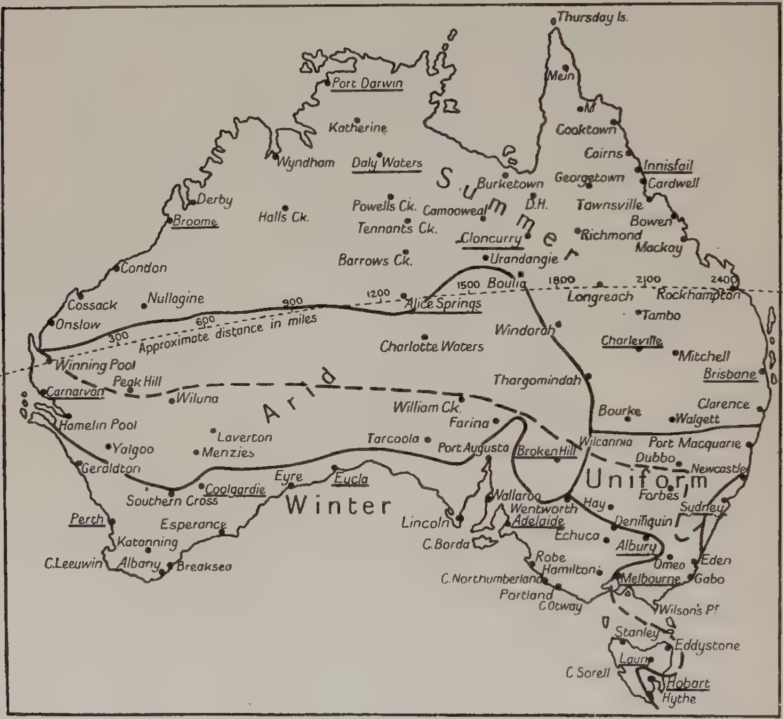

FIG. 229. Major Rainfall Regions. The broken line divides the summer and winter-rain regions. Localities underlined are those whose temperature and rainfall averages are given with appendix.

TYPES OF SUMMER RAIN REGION

Temperature.

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Broome, W.A.	85·8	85·3	85·3	83·2	76·2	71·6	70·4	72·6	77·0	80·9	84·5	86·0	79·9	14
Darwin, N.T.	84·0	83·4	84·1	84·2	81·9	78·9	77·2	79·5	82·7	85·5	85·7	85·3	82·7	29
Daly Waters, N.T.	86·8	85·5	83·8	80·4	74·7	70·4	68·6	72·8	79·8	86·1	88·3	88·1	80·4	25
Cloncurry, Q.	86·9	84·8	83·0	77·6	70·9	64·1	61·3	66·9	72·4	82·5	85·2	88·0	76·9	11
Charleville, Q.	82·8	80·2	75·8	68·8	60·2	53·5	51·0	56·5	62·8	71·6	77·4	80·2	68·4	9
Innisfail,[1] Q.	78·9	78·9	77·6	74·6	71·2	67·0	65·9	67·5	69·5	72·9	74·7	77·7	73·0	6
Brisbane, Q.	77·1	76·4	74·3	70·2	64·4	59·9	58·0	60·6	65·2	69·8	73·3	76·5	68·8	25

Rainfall[2]

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Broome, W.A.	505	615	355	141	43	127	28	4	8	4	97	355	2,282	22
Darwin, N.T.	1,541	1,310	980	436	79	16	7	11	48	213	524	1,047	6,212	41
Daly Waters, N.T.	629	680	507	98	15	36	7	16	27	87	207	416	2,725	38
Cloncurry, Q.	514	492	268	90	43	32	47	11	46	48	106	304	2,001	22
Charleville, Q.	258	327	335	152	147	119	77	61	84	130	138	229	2,057	22
Innisfail,[1] Q.	2,530	2,148	2,631	2,263	1,212	644	432	554	316	243	744	1,302	15,019	25
Brisbane, Q.	674	671	612	369	296	255	233	237	207	273	365	513	4,705	60

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[1] Innisfail is 50 miles south of Cairns.

[2] In points ; 100 points = 1 inch.

TYPES OF THE ARID REGION

Temperature.

Station.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Carnarvon, W.A. .	79·8	80·4	79·5	74·6	67·8	62·7	60·4	62·6	65·6	68·8	73·0	77·1	71·0	13
Coolgardie, W.A.	77·3	75·5	71·3	65·4	57·5	52·3	50·8	53·3	58·2	63·5	71·0	76·0	64·4	15
Alice Springs, N.T.	84·0	82·3	76·7	68·1	59·7	54·4	52·4	58·3	65·6	73·5	79·5	82·4	69·7	29
Broken Hill, N.S.W.	78·6	78·2	72·0	64·0	56·6	51·1	49·2	52·6	58·4	65·9	72·9	76·6	64·7	21

Rainfall.[1]

Station.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Carnarvon, W.A. .	31	72	47	53	127	291	184	65	26	8	4	9	917	29
Coolgardie, W.A.	38	72	62	62	134	123	85	94	63	69	54	64	920	19
Alice Springs, N.T.	176	171	130	94	63	59	43	41	43	75	89	125	1,109	37
Broken Hill, N.S.W.	75	67	66	79	86	125	61	99	70	82	57	62	929	22

TYPES OF UNIFORM RAIN REGION

Temperature.

Station.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Dubbo, N.S.W. .	78·7	77·3	70·9	64·1	55·2	49·4	47·4	50·5	56·1	63·4	70·7	76·3	63·3	35
Sydney, N.S.W. .	71·6	71·0	69·2	64·5	58·6	54·3	52·3	54·8	58·8	63·4	67·0	70·0	63·0	53
Melbourne, Victoria	67·5	67·2	64·7	59·6	54·1	50·3	48·5	51·0	53·9	57·5	61·3	64·5	58·3	56
Hobart, Tasmania .	62·0	62·2	59·4	55·4	50·6	47·1	45·7	48·1	50·8	54·0	57·3	59·8	54·3	28

Rainfall.[1]

Station.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Avge. for Year.*	*No. of Years.*
Dubbo, N.S.W. .	197	192	183	192	194	200	155	186	192	158	182	199	2,230	38
Sydney, N.S.W. .	367	469	507	524	495	518	468	329	289	282	291	260	4,799	53
Melbourne, Victoria	187	176	221	232	216	213	185	181	235	267	219	228	2,560	56
Hobart, Tasmania .	182	147	164	181	192	221	211	183	211	222	251	192	2,357	69

[1] In points; 100 points = 1 inch.

TYPES OF WINTER RAIN REGION

Temperature.

Perth, W.A.	73·5	74·1	71·1	66·4	60·4	56·2	55·0	55·9	58·0	60·9	65·4	70·6	64·0	15
Eucla, W.A.	70·8	71·1	69·3	66·1	60·8	55·9	54·3	56·2	59·2	62·7	65·9	69·2	63·5	33
Adelaide, S.A.	74·2	74·0	69·9	64·0	57·7	53·4	51·5	53·8	57·0	61·9	67·0	71·1	62·9	54
Albury, N.S.W.	76·2	74·3	69·3	60·4	52·1	47·8	45·9	49·0	53·8	60·1	66·9	71·9	60·7	43
Launceston, Tas.	64·1	64·5	60·6	55·5	49·1	46·5	44·1	46·3	50·2	53·9	58·2	62·0	54·8	18

Rainfall.[1]

Perth, W.A.	33	31	73	169	494	658	638	562	331	205	77	55	3,326	36
Eucla, W.A.	69	53	88	121	125	113	91	97	78	69	69	40	1,013	35
Adelaide, S.A.	81	57	115	183	282	301	259	238	178	179	105	84	2,062	54
Albury, N.S.W.	146	168	207	226	253	351	271	283	257	281	195	159	2,797	46
Launceston, Tas.	201	114	183	201	258	348	297	275	296	262	179	200	2,814	26

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[1] In points; 100 points = 1 inch.

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